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OPTIMIZATION IN THE DECOMMISSIONING OF URANIUM TAILINGS

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OPTIMIZATION IN THE DECOMMISSIONING OF URANIUM TAILINGS

ABSTRACT

This report examines in detail the problem of choosing the optimal decommissioning approach for uranium and mill tailings sites. Various decision methods are discussed and evaluated, and their application in similar decision problems are summarized.

This report includes, by means of a demonstration, a step by step guide of how a number of selected techniques can be applied to a decommissioning problem. The strengths and weaknesses of various methods are highlighted,

A decision system approach is recommended for its flexibility and incorporation of many of the strengths found in other decision methods.

RÉSUMÉ

Le présent rapport examine en détail la question du choix de l'approche de déclassement optimale dans le cas des sites de résidus des mines et usines de concentration d'uranium. Plusieurs méthodes y sont discutées et évaluées, et leur application à des problèmes de décision similaires y est résumée.

Le rapport contient aussi, à l'aide d'une démonstration, un guide pas-à-pas expliquant comment certaines techniques choisies peuvent être appliquées à un problème de déclassement. Les points et les faiblesses de diverses méthodes y sont mis en relief.

Une approche de système de décision est recommandée pour sa flexibilité et le fait qu'elle incorpore plusieurs des points forts qui se trouvent dans d'autres méthodes de décision.

DISCLAIMER

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TABLE OF CONTENTS

Abstract
List of Figures

1.0 INTRODUCTION 1

2.0 DESCRIPTION OF THE URANIUM MILL TAILINGS DECOMMISSIONING PROBLEM . 4
- 2.1 Description of the Reference Site 4
- 2.2 Decommissioning Options 6
- 2.3 Development of Criteria 8
  - 2.3.1 Health Impacts 10
  - 2.3.2 Cost Impacts 11
  - 2.3.3 Other Impacts 11

3.0 TECHNIQUES FOR EVALUATING TAILINGS DECOMMISSIONING OPTIONS 15
- 3.1 General Optimization Procedure 15
- 3.2 Description of Evaluation Techniques 18
  - 3.2.1 General 19
  - 3.2.2 Cost-benefit Analysis 19
  - 3.2.3 Cost-Effectiveness 20
  - 3.2.4 Mathematical Programming 21
  - 3.2.5 Decision and Utility Theory 22
  - 3.2.6 Multi-criteria Utility Techniques 23
  - 3.2.6 Fuzzy Sets 25
  - 3.2.7 Global Judgement 25
  - 3.2.8 Decision Systems 26
  - 3.2.9 Summary 27
- 3.3 Decision Techniques: Applications 28
  - 3.3.1 Overview 28
  - 3.3.2 Uranium Mine and Mill Tailings 29
  - 3.3.3 Low Level Radioactive Waste 32
  - 3.3.4 High Level Radioactive Waste 33
  - 3.3.5 Hazardous Waste 36
  - 3.3.6 Other Mine Wastes 38

3.3.7 Siting - Nuclear Power Plants 39
3.3.8 Other Waste Handling 41
3.4 Comparison of Evaluation Techniques 42
3.4.1 Factors for Comparing Evaluation Techniques 42
3.4.2 Feasible Evaluation Techniques 45

4.0 PERFORMANCE OF THE VARIOUS OPTIONS UNDER THE CRITERIA 49
4.1 Introduction 49
4.2 Health Impact Criteria 50
4.3 Cost Impact Criteria 54
4.4 Other Impact Criteria 55

5.0 APPLICATION OF DECISION METHODS 57
5.1 Overview 57
5.2 Cost Benefit - As a Procedure 58
5.2.1 Overview 58
5.2.2 Details of Main Steps 60
5.3 Cost-Effectiveness 66
5.3.1 Overview 66
5.3.2 Details of Main Steps 66
5.4 Multi-Attribute Utility Theory 68
5.4.1 Overview 68
5.4.2 Detailed Procedure 71
5.5 Decision System 77
5.5.1 Overview 77
5.5.2 Detailed Example of Decision System 78

6.0 CONCLUSIONS AND RECOMMENDATIONS 81

7.0 REFERENCES 82

Appendix I Disposal Options and Judgements about the Future
Appendix II Project Evaluation and Decision Processes
Appendix III Decision Techniques: Applications
Appendix IV Annotated Bibliography

List of Figures

	Title	Follows Page
Figure 1:	Overview of Report Contents	2
Figure 2:	Schematic Illustration of Watershed Setting for the Reference Tailings Site	4
Figure 3:	Cross - section view of Reference Tailings Site Showing Groundwater and Surface Water Flow Component	4
Figure 4:	Evaluation Criteria	13
Figure 5:	Tailings Decommissioning Optimization Process	15
Figure 6:	Reference Site: Overview	50
Figure 7:	Dose vs. Time By Pathway (Scenario 1)	52
Figure 8:	Drinking Water Dose vs Time by Radionuclide (Scenario 1)	53
Figure 9:	Performance of Options Under Criterion Air Quality	56
Figure 10:	Performance of Options Under Criterion Public Acceptability	56
Figure 11:	Performance of Options Under Criterion Material Requirements Impact	56

Figure 12:	Performance of Options Under Criterion International Acceptability	56
Figure 13:	Performance of Options Under Criterion Land Usage	56
Figure 14:	Performance of Options Under Criterion National Interest	56
Figure 15:	Performance of Options Under Criterion Aesthetics	56
Figure 16:	Performance of Options Under Criterion Provincial Interest	56
Figure 17:	Performance of Options Under Criterion Institution Control Requirements	56
Figure 18:	Performance of Options Under Criterion Local Impacts (Employment)	56
Figure 19:	Performance of Options Under Criterion Local Impacts (Other)	56
Figure 20:	Performance of Options Under Criterion Reliability	56
Figure 21:	Performance of Options Under Criterion Natural Barriers	56
Figure 22:	Performance of Options Under Criterion Flexibility	56
Figure 23:	Performance of Options Under Criterion Experience	56

Figure 24: Performance of Options Under Criterion Complexity 56

Figure 25: Performance of Options Under Criterion Volume Reduction 56

Figure 26: Performance of Options Under Criterion Wildlife (Terrestrial) 56

Figure 27: Performance of Options Under Criterion Wildlife (Aquatic) 56

Figure 28: Performance of Options Under Criterion Water Quality 56

Figure 29: Costs - As and Ni at Time = 500 years 62

Figure 30: Costs - Radiation at Time = 500 years 62

Figure 31: Costs - As Ni and Rod at Time = 500 years 62

Figure 32: Cost vs. Cancer - Aresenic and Nickel at Time = 500 years 66

Figure 33: Cost vs. Cancer - Radiation at Time = 500 years 66

Figure 34: Cost vs. Cancer - As, Ni and Radiation at Time = 500 years 66

1.0 INTRODUCTION

There are several licensed uranium mill tailings sites in Canada that are presently in need of decommissioning and many more that will require decommissioning in the near future. There are several decommissioning options that are feasible for each tailings site. Tools are necessary to assist the decision-maker in choosing from among the viable decommissioning options for a particular uranium tailings site. It is the purpose of the present report to evaluate some of the viable decision-making techniques and to summarize the application of these techniques in related industries and problems. This report also includes, by means of a demonstration, a step by step guide of how the selected techniques can be applied to a typical uranium mill tailings decommissioning problem.

Optimization in this report refers to the process of choosing the "best" decommissioning option for a uranium mill tailings site. As part of this process, one or more evaluation techniques (such as cost-benefit, cost-effectiveness, and multi-criteria analysis) may be used to allow comparison and ranking of the various considered options. Optimization of radiation exposure as is used in the application of the ALARA (As Low As Reasonably Achievable) principle may be a part of the overall optimization process.

The optimization process should provide a systematic method by which the decision-maker can assemble and review necessary information and manipulate this information into a form that will provide a clear defensible framework for selecting an option for the decommissioning of uranium tailings.

There are several kinds of decisions that have to be made about projects ranging from a decision on whether or not to proceed with a single project through to the problem of allocating resources to several competing projects. The tailings decommissioning problem is one of selecting one option from a number of available choices. An essential part of the process of choosing is to evaluate the alternatives in a way that allows their "value" to be compared. The method of evaluation may be quantitative, qualitative, or a combination. Also the measure of value may be monetary units or monetary units in combination with other measures of value. Furthermore, the objectively measured or estimated values may be combined with other factors in the decision process as will be discussed in chapter 3.

This report is structured as shown in the flow diagram in Figure 1.

Chapter 2 gives a description of the decommissioning options used as examples in this study. These are given for a typical uranium mill tailings site in northern Ontario. As well, the evaluation criteria, relevant to the problem, are developed.

Chapter 3 presents a description of various evaluation techniques, the use of evaluation techniques in various related fields, and a comparison of the various evaluation techniques with respect to selected factors. A selection of techniques used in the tailings application, described in chapters 4 and 5, is made.

Chapter 4 contains a discussion of the performance of the decommissioning options under the various criteria developed in chapter 2. These performance values are used in the application of the various evaluation techniques that is described in chapter 5.

Chapter 5 contains the application of the selected evaluation techniques to the decommissioning options.

Chapter 6 contains a discussion of the applicability of the various techniques and recommendations concerning their use.

Appendix I contains a discussion by Dr. R.V. Osborne of future discounting and truncation of impact with respect to time, magnitude and space.

Appendix II contains a discussion by Professor J.E. Dooley of evaluation

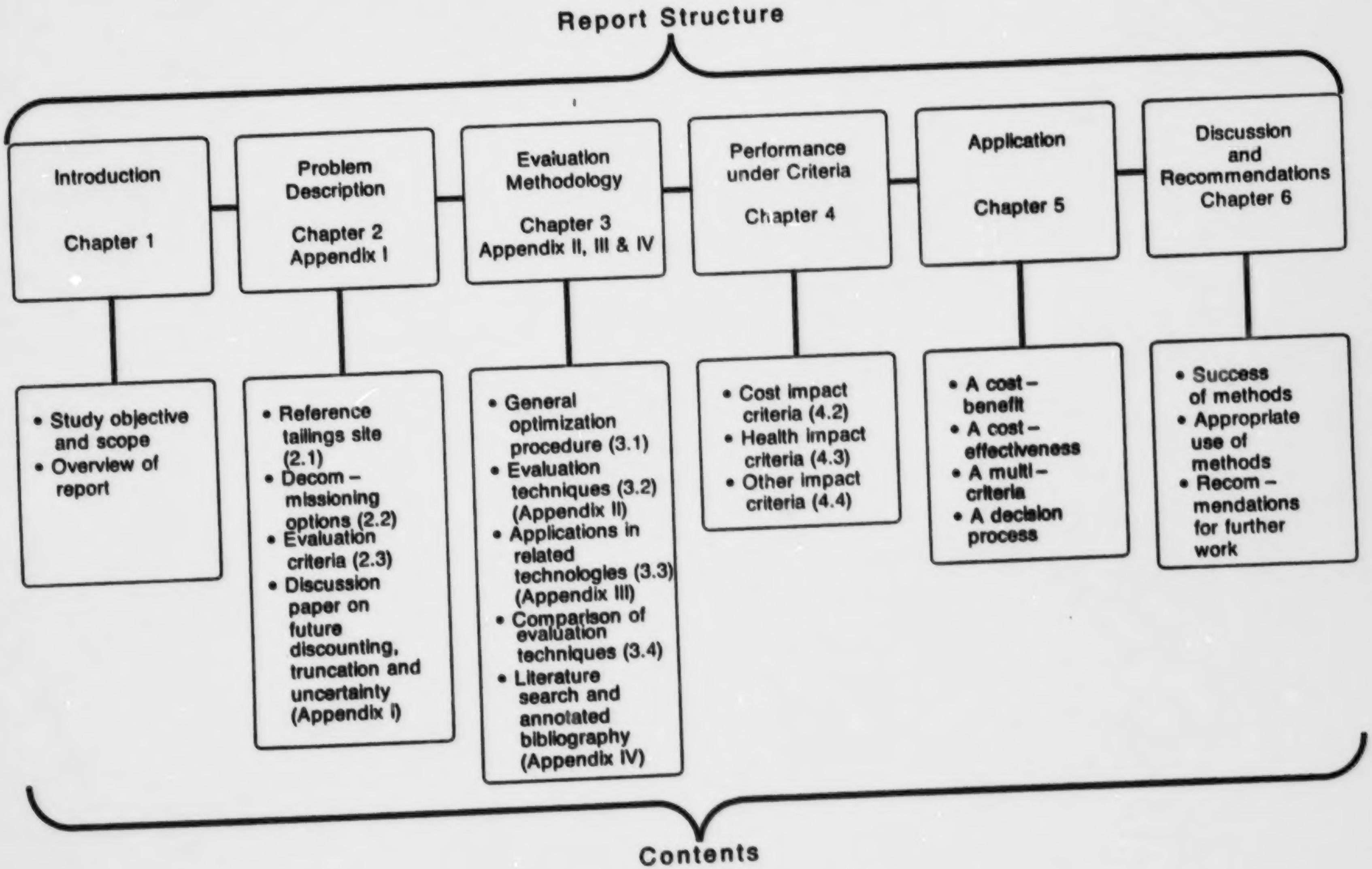
Report Structure
Introduction
Chapter 1
Problem Description
Chapter 2
Appendix I
Evaluation Methodology
Chapter 3
Appendix II, III & IV
Performance under Criteria
Chapter 4
Application
Chapter 5
Discussion and Recommendations
Chapter 6
• Study objective and scope
• Overview of report
• Reference tailings site (2.1)
• Decom – missioning options (2.2)
• Evaluation criteria (2.3)
• Discussion paper on future discounting, truncation and uncertainty (Appendix I)
• General optimization procedure (3.1)
• Evaluation techniques (3.2) (Appendix II)
• Applications in related technologies (3.3) (Appendix III)
• Comparison of evaluation techniques (3.4)
• Literature search and annotated bibliography (Appendix IV)
• Cost impact criteria (4.2)
• Health impact criteria (4.3)
• Other impact criteria (4.4)
• A cost – benefit
• A cost – effectiveness
• A multi – criteria
• A decision process
• Success of methods
• Appropriate use of methods
• Recom – mendations for further work
Contents

Figure 1

Overview of Report Contents

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techniques that are available for use in a decision process.

Appendix III contains a summary of the results of the literature search for applications of evaluation techniques in the nuclear industry and other related industries.

An annotated bibliography, of the searched literature, is contained in Appendix IV.

2.0 DESCRIPTION OF THE URANIUM MILL TAILINGS DECOMMISSIONING PROBLEM

2.1 Description of the Reference Site

In order to demonstrate the application of the evaluation techniques to a typical Canadian uranium mill tailings decommissioning problem, the tailings area was chosen to be the generic site considered in the National Uranium Tailings Program (NUTP) modelling program [1]. This site was chosen to reflect the major environmental features pertinent to tailings on the Canadian precambrian shield. While the pathways and the decommissioning options may vary for different tailings sites, the application of the optimization process to the generic site should provide an adequate demonstration of the process. The generic site and the main contaminant release pathways are shown in Figures 2 and 3.

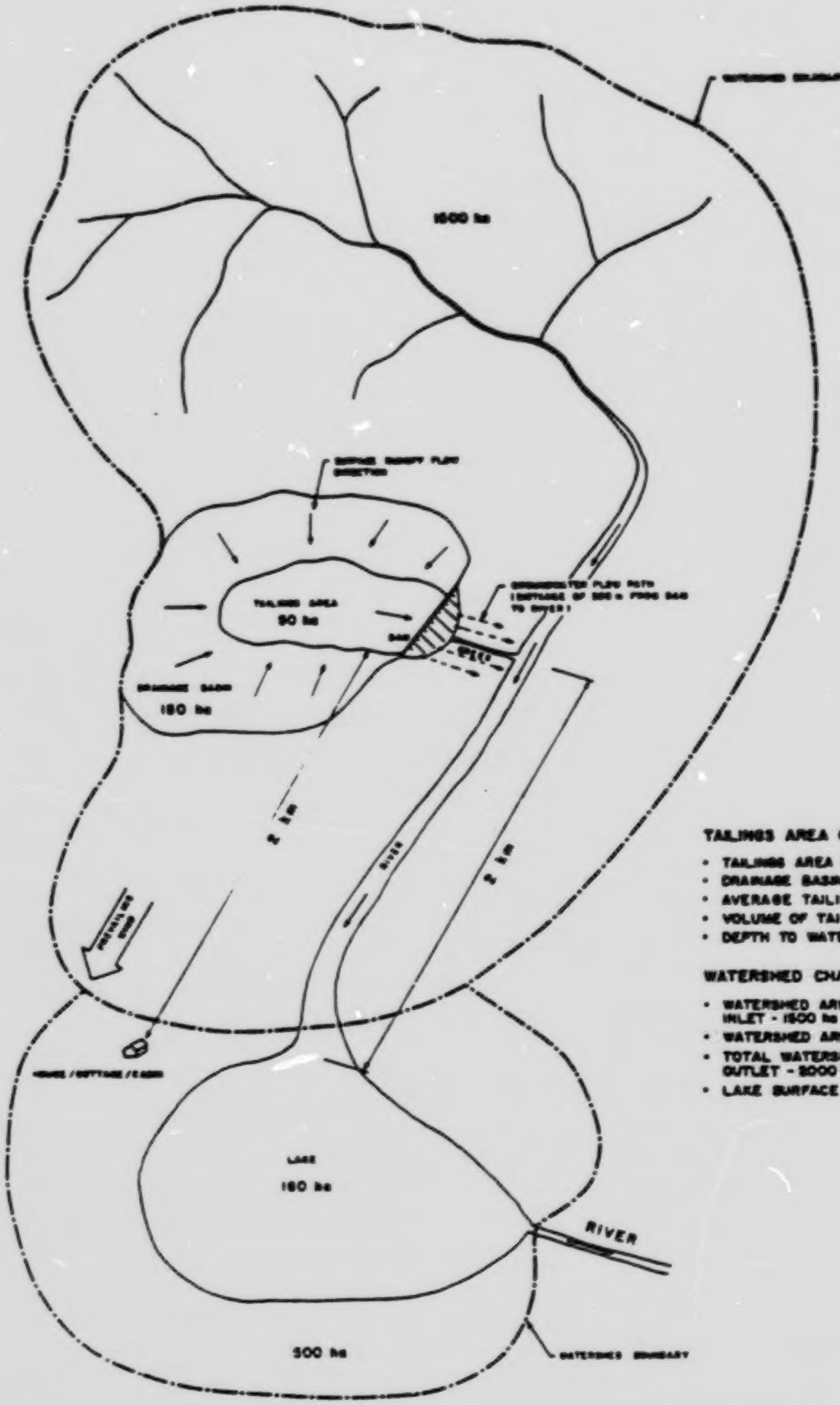
A previous NUTP report [2] characterizes the site by: "The tailings disposal site was taken to occupy a natural depression formed within the upper reach of a valley, that is, a land/shallow-water type site. The tailings were considered to be contained behind a conventional dam constructed across the low point. The reference tailings site was defined to have a surface area of 50 ha and an average tailings depth of 10 m, for a total volume of 5.0E+06 m3. The drainage basin containing the tailings was assumed to be 150 ha in area (including the tailings)."

Details of the physical, chemical and radiological characteristics of the tailings are given in the NUTP report [2]:

"The reference tailings have characteristics representative of those resulting from the acid leaching of low-grade pyritic uranium ores containing approximately 0.1% uranium. Ninety-five percent of the uranium is assumed to be recovered during milling, while all of the other radionuclides are assumed to remain with the tailings.

SCHEMATIC ILLUSTRATION OF WATERSHED SETTING FOR THE REFERENCE TAILINGS SITE

(from Ref. 2)


1500 ha
50 ha
150 ha
2 km
2 km
RIVER
150 ha
RIVER
500 ha

TAILINGS AREA CHARACTERISTICS:

- TAILINGS AREA SIZE - 50 ha
- DRAINAGE BASIN SIZE - 150 ha
- AVERAGE TAILINGS DEPTH - 10 m
- VOLUME OF TAILINGS - 5 x 10^6 m^3
- DEPTH TO WATER TABLE IN TAILINGS - 1 m

WATERSHED CHARACTERISTICS:

- WATERSHED AREA OF RIVER TO LAKE INLET - 1500 ha
- WATERSHED AREA OF LAKE - 500 ha
- TOTAL WATERSHED AREA TO LAKE OUTLET - 2000 ha
- LAKE SURFACE AREA - 150 ha

FIGURE 2

CROSS-SECTIONAL VIEW OF REFERENCE TAILINGS SITE
SHOWING THE GROUNDWATER AND SURFACE WATER FLOW COMPONENT
(from Ref. 2)

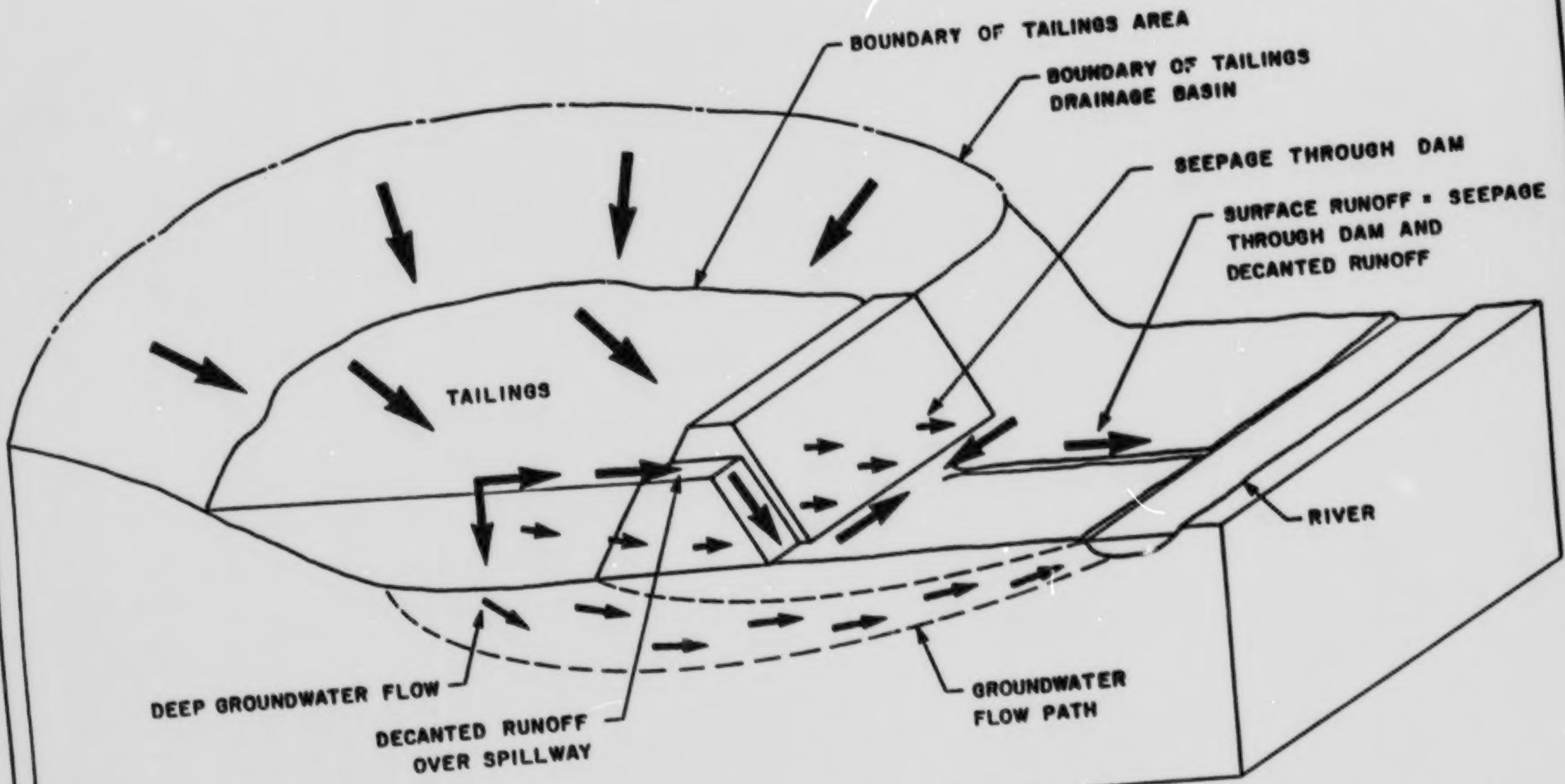

BOUNDARY OF TAILINGS AREA
BOUNDARY OF TAILINGS DRAINAGE BASIN
SEEPAGE THROUGH DAM
SURFACE RUNOFF = SEEPAGE THROUGH DAM AND DECANTED RUNOFF
TAILINGS
RIVER
DEEP GROUNDWATER FLOW
DECANTED RUNOFF OVER SPILLWAY
GROUNDWATER FLOW PATH

FIGURE 3

Specifically, the principal characteristics of the tailings are: a particle size distribution of 50% less than 75 um; a pyrite content of 6.5%; a gypsum content of 5%; and, a radium concentration of 5 to 15 Bq/g distributed between tailings solids and gypsum."

Although the generic, precambrian tailings site discussed above does not contain nickel or arsenic, for the purposes of the current study, it was assumed that the tailings contained both of these elements. Resulting leachate concentrations were obtained from modeling results reported 3. The arsenic and nickel were assumed to be in the tailings, to demonstrate handling of non- radiological impacts in the evaluation techniques.

Calculation of health impacts from the tailings site is necessary because of the potentially hazardous nature of the contaminants in the tailings.

The major pathways of contaminant release from the tailings are the following:

- decant of excess runoff via a spillway to the creek,
- seepage through the dam into the creek,
- seepage into the groundwater system (approx. 10% of precipitation) and transport to the river,
- airborne transport of radon and particulate contaminants (prevailing wind is in the direction of the river flow).

Public health impacts from these contaminants results from the transport of the contaminants into the air and water environment that are normally used by the public. Typical public health impact analyses consider the impact both to an individual member of a critical receptor group and to local and regional population groups. The impact to the global population may also be considered in an analysis but is not considered in this study.

The critical receptor group was assumed to be situated at a point 2 km down wind and down river from the tailings site.

The critical receptor was assumed to be an adult male who obtains his drinking water from the first lake downstream of the tailings site, and lives off the land consuming only locally grown vegetables, meat (caribou and moose), and fish. An external exposure pathway (groundshine) from air deposited radioactive contaminants was also considered.

For the purposes of the present study it was assumed that a local population of 5,000 live within 10 km of the site (a town 10 km downwind of the site) and a regional population of 50,000 live within 50 km of the site (45,000 in a small city 50 km downwind of the site). Two other lakes (details in ref.1) were also assumed at downstream locations from the first lake. The regional population groups were assumed to be exposed to airborne contamination and to use only drinking water from the tailings watershed.

2.2 Decommissioning Options

In order to control contaminant releases from the tailings site after its active service life, various decommissioning options are available.

Generally, the selection of decommissioning options for a uranium tailings site is governed by some basic constraints. These include the following:

- the option must be technically and economically feasible,
- the estimated doses and contaminant concentrations in water and air must not exceed the applicable regulated limits.

The options selected for use in this study are not intended to be an exhaustive list of decommissioning options, rather a representative spectrum of feasible options that are used to demonstrate the application of the evaluation techniques. Combinations of these options are not considered. Such combinations would have to be considered as separate and independent decommissioning options.

The options for decommissioning the reference uranium tailings site that are considered in this study are the following:

Option 1 The base case to be considered in this study is the "do-nothing-additional" option. The tailings area is left uncovered and no further attempt is made to control runoff or seepage.

Option 2 A pyrite reduction circuit is added to an existing mill to produce pyrite-reduced tailings. Limestone is added in stochiometric proportions to control acidity. These treated tailings are then used to provide a one meter cover over the existing tailings.

Option 3 Limestone and fertilizer are added directly to the tailings. The amount of limestone added is sufficient to neutralize the pyrite in the top one meter of tailings. The surface is graded, shaped, vegetated and surface drainage control is provided.

Option 4 A three meter cover of borrow soil is placed on the tailings and vegetated.

Option 5 This is the same as option 4 and, in addition, a grout curtain is added to the dam to prevent seepage through the dam.

Option 6 The tailings, dams and a 3 m layer of underlying soil are relocated to an equivalent basin constructed with a three meter cover of borrow soil and an impermeable grouted dam. The tailings are excavated with drag lines, hauled by trucks on existing roads and placed by trucks into the engineered basin and covered with one meter of soil/bentonite and vegetated. The relocated tailings disposal area is chosen to be remote from any surface water body likely to be used as a drinking water source.

Option 7 A treatment plant is maintained and operated in perpetuity to treat seepage groundwater and surface runoff. Continued maintenance to the existing dams is also included.

Details of the seven options are given in Chapter 4.

2.3 Development of Criteria

The uranium tailings decommissioning problem which has been outlined in the preceding section is characterized by a number of relevant aspects, some unique to this problem. From these specific aspects of the problem, a comprehensive set of criteria, useful in the optimization process, can be generated. Not all of the criteria may be used in the optimization, depending on which evaluation techniques are employed; however the full set is presented here so that the decommissioning problem may be fully characterized.

The major aspects of the decommissioning problem can be discussed under three major headings: health impacts, cost impacts and other impacts. These are discussed in the following sections.

There are three important features of the analysis of the impacts from uranium tailings decommissioning that must be taken into consideration in the optimization of decommissioning options. These are: (1) the time of occurrence of the impacts, (2) the absolute magnitude of the impacts, and (3)the magnitude of the uncertainty of the projected impacts. These features are discussed briefly here, and more fully in Appendix I.

The time of occurrence of the projected impact is important in that the following question is raised. If the maximum impact from one option occurs within a relatively short span of time, whereas, that from another option occurs in the distant future and if the magnitudes of the impacts are equivalent, which option will be preferable? Should there be some form of discounting of future impacts? This question is pertinent in uranium tailings decommissioning since long time scales are involved (i.e. hundreds of years). Since our predictive abilities over those time periods are questionable; and generally, become more uncertain for longer time periods, how far is it reasonable to conduct calculations, and therefore which time periods should be used in the optimization process? Appendix I contains a discussion of some of the current views on this question. The effect of these views on the optimization process will be discussed in chapters 4 and 5.

The absolute value of the impacts poses two diametrically opposite questions. For example, if the maximum reasonable individual dose is above the current dose limit, should the option be considered further? The answer to this question is usually "No!", since in this case one of the basic constraints in the selection of options is violated. The optimization process may incorporate the application of the ALARA principle which serves to ensure that the maximum individual risk to radiation exposure is as far below the exposure limit as practical. The other side of the problem is that since zero risk is impossible, which value of risk can be considered to be negligible and therefore not included in a population risk calculation? This is especially pertinent in the consideration of global risks. This question is also discussed in Appendix I and the effect of the different views on the optimization process will be discussed in chapters 4 and 5.

The uncertainty of the impact estimates can be useful in comparing options. If there is a difference in impacts, the significance of that difference can be determined. When probabilistic analyses have been carried out in the determination of the risks, various parameters describing the distribution of the risk estimate can be used in the optimization (e.g. median, mean, standard deviation, information about the low probability tail). The use of uncertainty estimates in the optimization process will be discussed in chapters 4 and 5.

2.3.1 Health Impacts

The health impacts can be subdivided into two major categories, those from radiological contaminants and those from non-radiological contaminants. These can be further sub-divided into risks to the public and occupational risks. In general, public risks are estimated from a pathways analysis in which the impacts along various routes by which the contaminants reach man are evaluated. The uptake of radioactive contaminants is expressed as a dose (in Sv/a), whereas that of non-radioactive contaminants is expressed in terms of the body burden of each specific contaminant. These doses can be converted into other units to allow comparison. Examples of other units would be risk of loss of life from cancer or years of life lost.

Public risk may result from both chronic releases of contaminants and releases following extreme events (such as a dam failure) and may be expressed both as risks to an individual in a critical receptor group or a population group (local, regional, global). There are different methods of combining these risks and these will be discussed in chapter 4.

Occupational risks are determined in a manner similar to public risks as the work procedures and the contaminant concentrations at the various work locations are determined. Contaminant uptakes are determined and the resultant risks to the most exposed worker and worker groups are calculated. The impact, as years of life lost due to conventional accidents (falls, traffic accidents etc) must also be considered as part of the occupation risk.

As discussed in the previous section, consideration must be given to the time of occurrence of the risks, the magnitude of the risks and the magnitude of the uncertainty associated with the risks.

2.3.2 Cost Impacts

The costs encompass the capital and the operating costs of a decommissioning option and any provision for potential future failure of the tailings containment system (e.g. insurance policy, sinking fund).

The capital costs can be broken into labour, materials and transportation costs. The operating costs can be further broken into monitoring, maintenance, system operation, and system labour. Operating costs are usually only a small percentage of the costs for the decommissioning options requiring minimal long-term maintenance. However, these costs comprise the largest component of the cost for an option, such as option 7, requiring a long term, active maintenance option.

As well, numerous assumptions are required for long term cost projections concerning the stability of financial institutions, value of capital, value of labour etc. These uncertainties grow in magnitude as the time projections are extended further into the future. These uncertainties must be considered when evaluating options.

2.3.3 Other Impacts

The impacts in this section are usually either difficult to quantify on a common basis, or difficult to quantify objectively. These include certain environmental effects, certain technical effects that are qualitative in nature, and social/political effects.

The environmental effects include water quality parameters such as pH and biochemical oxygen demand (BOD), air quality parameters such as suspended particulates and dustfall, and the effect of the decommissioned tailings on terrestrial and aquatic wildlife. The parameters such as pH and BOD are important only as far as they affect the natural ecosystem and the degree to which they may fall outside ranges that are acceptable. Ranges of pH that are common in an undisturbed environment lie between 4 and 9. It is found that water of pH outside the range of 6.5 to 9 will affect the aquatic environment and that of pH outside the range 6.5 to 8.3 is considered unsuitable for drinking.

BOD is not a pollutant in itself; however, it serves to indicate the level of organic pollution. Waters in which the BOD is less than 4 mg/L are considered reasonably clean. Those with a BOD greater than 10 mg/L are considered polluted.

Other indicators of water quality are heavy metal concentrations, salinity, total dissolved and suspended solids, and major ion concentrations. The water quality parameters are important in the optimization of tailings decommissioning options only as far as they affect the natural ecosystem.

The major contributors to the air quality in the vicinity of the decommissioned tailings other than the contaminant concentrations would be the suspended particulate levels and perhaps the dustfall. These levels can be compared with ambient air quality standards of 100 ug/m3.

The overall effect of the decommissioning options on terrestrial and aquatic wildlife must also be considered in the decision process.

The technical characteristics such as reliability, reliance on natural barriers, flexibility to cope with future change, previous experience, and complexity are important in evaluating the various decommissioning options.

An example of this is reliance on natural barriers. Greater confidence is usually given to natural barriers acting as containment barriers. For example, a system which makes exclusive use of natural barriers would be desirable, whereas one which uses only artificial barriers (e.g. liners) to result in the same release rate would be less desirable.

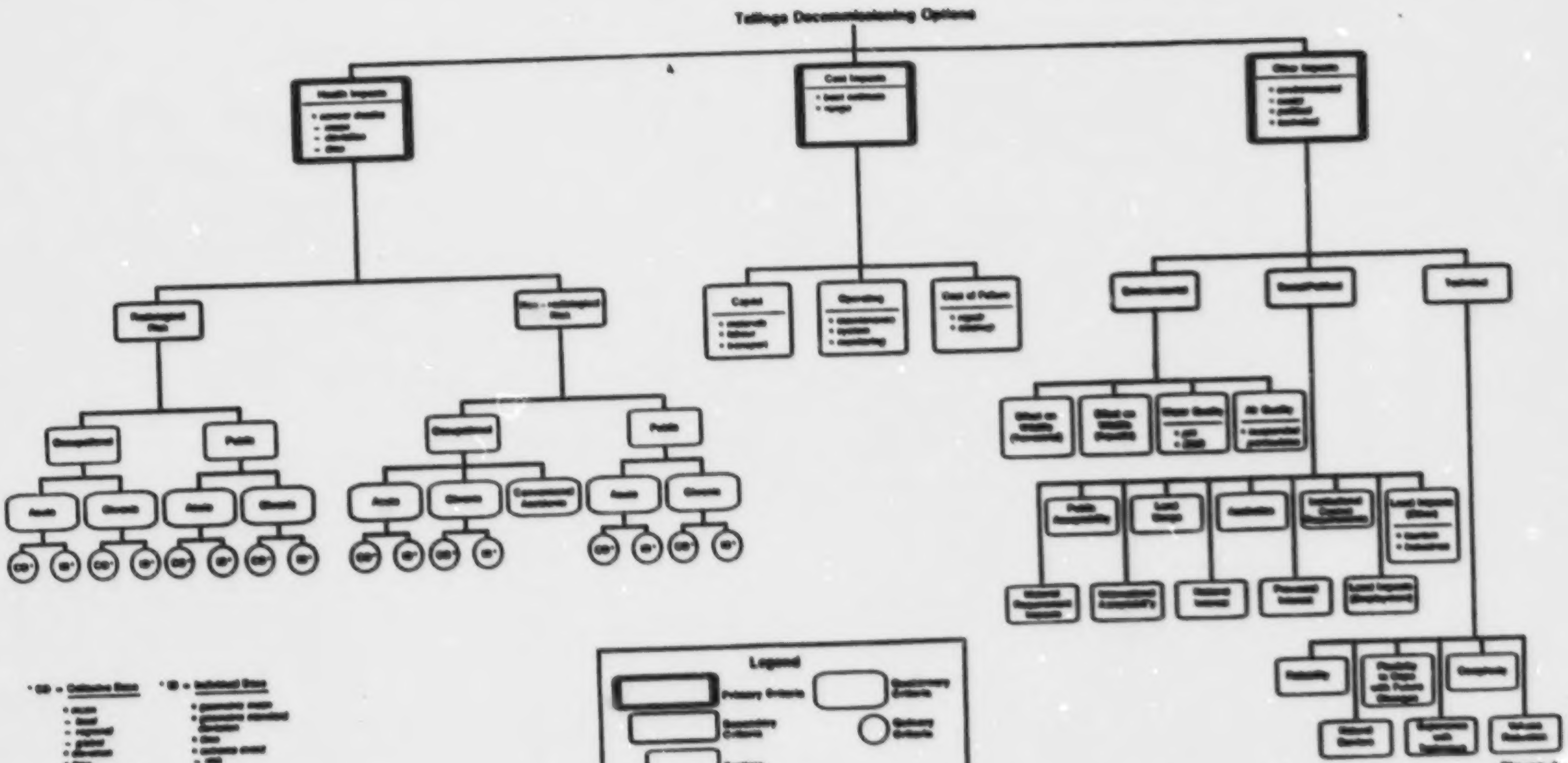
The social/political impacts include employment during the decommissioning and operation of the site, land usage, degree of local, provincial, and national interest, acceptability of the option to the international community, scientific community, the regulators, and the public, aesthetics, material requirements impacts, local economic and social impacts. These factors can, under certain decommissioning scenarios be important.

In the discussions above, a number of characteristics describing the various aspects of the decommissioning problem were considered. In order to evaluate and compare each of the decommissioning options, these characteristics have been used to develop a set of criteria. The criteria reflect the basic characteristics of the tailings decommissioning problem given above and represent the aspects of the tailings decommissioning problem for which value judgements may have to be made. The criteria can be set up in a hierarchical structure to make all the value judgements transparent (e.g. figure 4).

A measure can then be used to quantify the performance of each option under a particular criterion. The units of measure depend, not only on the criteria, but on the evaluation technique. This will be discussed for each technique in the following chapters.

The criteria are presented in Figure 4 in a hierarchical structure along with some of the data that are necessary to determine the performance under the criteria for a decommissioning option. The three main branches are the health impacts, the cost impacts and other impacts. The cost impacts branch is structured with two levels of criteria (primary and secondary), the other impacts branch has three levels (primary, secondary, and tertiary) and the health effects branch has five levels (primary, secondary, tertiary, quaternary and quinary).

Each hierarchical level represents the aggregation of criteria from the level below. The lowest level represents criteria for which no aggregation was necessary and represents the most detailed level of criteria upon which a decision between options may be made. The reason that the health impact


Tailings Decommissioning Options
Health Impacts
Cost Impacts
Other Impacts
Capital
Operating
Cost of Failure
Occupational
Public
Acute
Chronic
CD*
ID*
Air Quality
Water Quality
Technical
Legend
Primary Criteria
Secondary Criteria
Tertiary Criteria

Figure

Evaluation Criteria

branch has five hierarchical levels whereas the cost impact branch has only two reflects the fact that value judgements may be made at greater levels of detail (i.e. less aggregation) for health impacts than for cost impacts. In the case of the other impacts branch, there could be many more hierarchical levels, but since there is so much qualitative and subjective input, a further subdivision would not necessarily make the evaluation more transparent.

Evaluation techniques such as cost-benefit analysis would use only the primary criteria; whereas, those such as multi-criteria analysis could use all the hierarchical levels, although the decision would likely be made at the primary level. For example, in the case of a multi-criteria analysis, if there is insufficient difference between options at the primary criteria level, the decision maker could then consider differences at the secondary criteria level and so on.

It should be noted that Figure 4 is but an example of the hierarchical structure. Other structures are possible. For example, in the case of the health effects branch, occupational and public risk might be secondary criteria, with radiological and non-radiological risks becoming tertiary criteria. An example of how this might be done in practice and the effects on the decision process is given in the applications section (Chapter 5).

3.0 TECHNIQUES FOR EVALUATING TAILINGS DECOMMISSIONING OPTIONS

3.1 General Optimization Procedure

This section will begin with a brief description of a general procedure for creating decommissioning options, for evaluating them, and for choosing among them. This procedure gives a framework to put the evaluation techniques into perspective because the evaluation is only part of the process of determining a decommissioning option. The procedure will also set the stage for the discussion of the evaluation techniques given in the next section.

A flow diagram showing the main stages is given in Figure 5. The diagram gives the main inputs to each stage and the main outputs. It is assumed that in practice there will be a number of recycling stages as the options become refined and their performance better understood.

A. Tailings Decommissioning options

The process begins with the creation of decommissioning options. The options of interest in this report were discussed in section 2.2. A description of the options and the location must be input to the next stage where the options are screened.

B. Preliminary evaluation

In this stage preliminary estimates of the risks, costs, and benefits are made for each of the disposal options described in stage A. The estimates will be made using simple prediction models combined with expert judgement. This stage, combined with the next stage is often called a feasibility study.

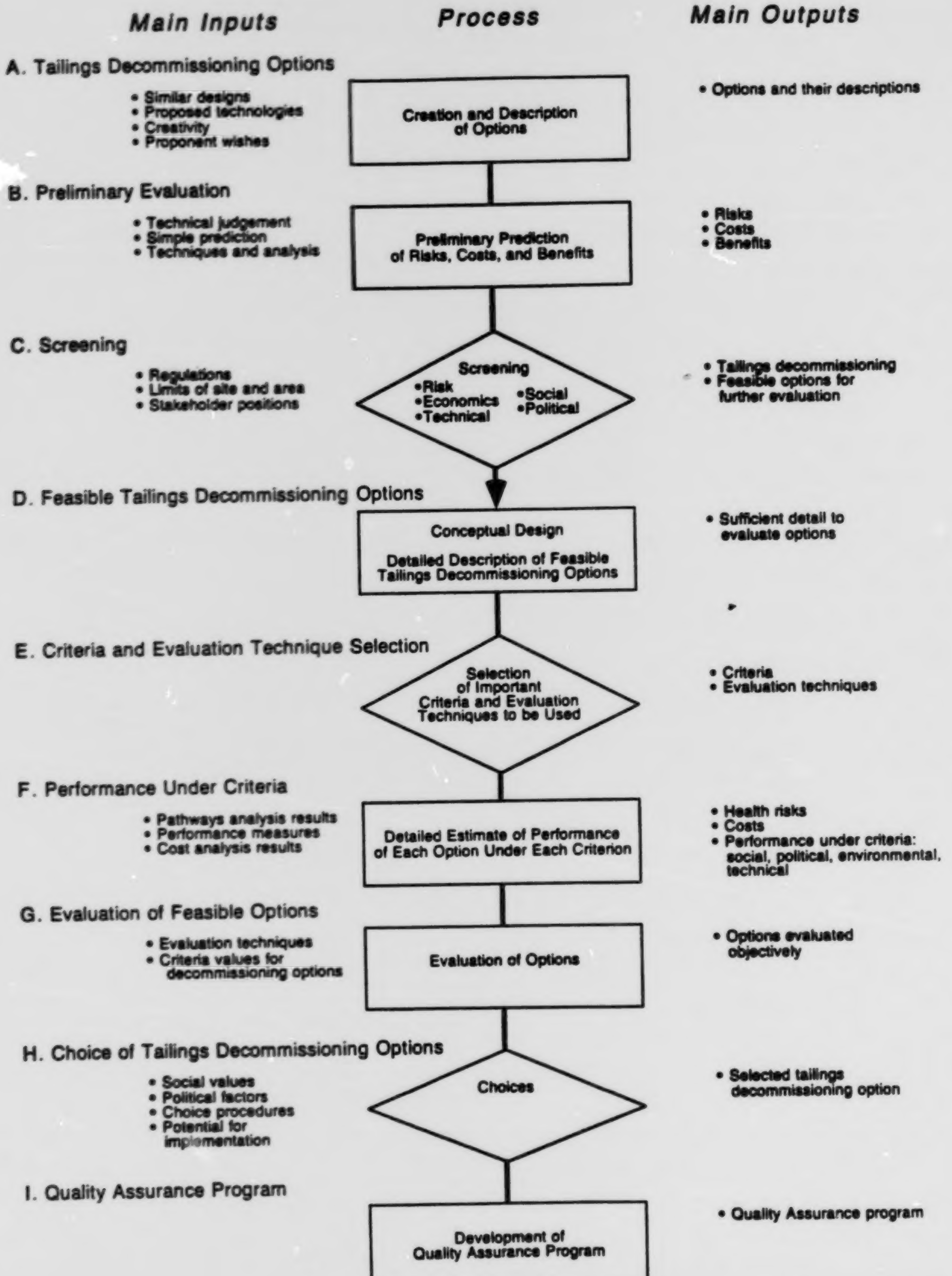

Main Inputs
Process
Main Outputs
A. Tailings Decommissioning Options
• Similar designs
• Proposed technologies
• Creativity
• Proponent wishes
Creation and Description of Options
• Options and their descriptions
B. Preliminary Evaluation
• Technical judgement
• Simple prediction
• Techniques and analysis
Preliminary Prediction of Risks, Costs, and Benefits
• Risks
• Costs
• Benefits
C. Screening
• Regulations
• Limits of site and area
• Stakeholder positions
Screening
•Risk
•Economics
•Technical
•Social
•Political
• Tailings decommissioning
• Feasible options for further evaluation
D. Feasible Tailings Decommissioning Options
Conceptual Design
Detailed Description of Feasible Tailings Decommissioning Options
• Sufficient detail to evaluate options
E. Criteria and Evaluation Technique Selection
Selection of Important Criteria and Evaluation Techniques to be Used
• Criteria
• Evaluation techniques
F. Performance Under Criteria
• Pathways analysis results
• Performance measures
• Cost analysis results
Detailed Estimate of Performance of Each Option Under Each Criterion
• Health risks
• Costs
• Performance under criteria: social, political, environmental, technical
G. Evaluation of Feasible Options
• Evaluation techniques
• Criteria values for decommissioning options
Evaluation of Options
• Options evaluated objectively
H. Choice of Tailings Decommissioning Options
• Social values
• Political factors
• Choice procedures
• Potential for implementation
Choices
• Selected tailings decommissioning option
I. Quality Assurance Program
Development of Quality Assurance Program
• Quality Assurance program

Figure 5

Tailings Decommissioning Optimization Process

43479

C. Screening

The purpose of the screening stage is to select the options that are considered feasible and should be considered further as possible solutions to the tailings decommissioning problem. There are many dimensions to feasibility. Options are risk feasible if they can be designed to make the risk "acceptably small". It may be desirable to eliminate those that are clearly very risky or difficult to predict or control. Economic feasibility means that the costs are within acceptable bounds and no option costs considerably more than the others for about the same risk. Technical feasibility is concerned with selecting the options for which design, construction, and operating technology exists or can be created. Technical feasibility also requires that the options meet the applicable regulations. Options are socially feasible if they stand a good chance of being accepted by society either based on some principle or simply by gaining the approval of society. Political feasibility means that they have a chance of passing the political hurdles after going through the evaluation and approvals processes.

The inputs to the screening stage are the descriptions of the options, the applicable regulations, the preliminary evaluations, and the stakeholder's positions. Stakeholders are the people and organizations responsible for the decision or affected by it. The product is a set of feasible tailings decommissioning options that are retained for further evaluation. Some options may be feasible but others in the set are as good in some respects and better in others and so "dominate" them. Dominated options should also be eliminated at this stage.

D. Detailed descriptions.

This stage is not strictly part of the decommissioning decision procedure but is necessary to provide the information for the next stage. The stage requires a more detailed conceptual description of the options be developed and a more detailed analysis of health and environmental impacts. For example, risk analysis and cost analysis are a few of the tools used at this stage.

E. Selection of Evaluation Techniques and Criteria

The evaluation techniques to be used and the criteria to be considered in the detailed evaluation of the decommissioning options are selected at this stage. It is important to have a good knowledge of the relative importance of the criteria at this stage to ensure that the proper evaluation technique(s) is (are) chosen.

F. Performance under Criteria

In this stage the performance of each option under each of the criteria has to be determined. Data from Stage D is used. If cost is one of the criteria then the "performance" of an option is the cost of that option. Similarly if risk, as measured possibly by chronic cancers, is a criterion, then the predicted cancers for an option would be it's performance under this criterion. It is important to note that performance can be expressed qualitatively with verbal expressions of performance in the form of single words such as high, medium or low or sentences. If reasonable grounds exist for expressing the performance quantitatively, then a quantitative measure of performance is preferred.

G. Evaluation of Options

The technique(s) for evaluating options is(are) applied in this stage. The purpose of the evaluation stage is to integrate the inputs into an expression of the suitability of the options. The criteria and the performance of each option under each criterion are inputs. The output is an evaluation of each option. In general, this should be an objective evaluation even though subjective inputs are necessary. The decision-makers are treated at this stage as acting in an objective way on behalf of society so it is in this sense that their values are objective.

H. Choice

The results of the evaluation are combined with other factors, not explicitly contained in the evaluation, such as political and social factors that were not incorporated into the evaluation stage. This may involve public hearings, or a hearing board, or simply a responsible committee or individual. The output is the choice of a recommended method for tailings decommissioning. There may be conditions attached to the choice that will have to be incorporated.

I. Quality Assurance Program

A quality assurance program should be a part of the overall ongoing optimization process to ensure that the data are accurately used in the evaluation and that the process is properly executed and documented. In addition, the quality assurance program should be part of the conditions for acceptance of an option. This would entail such actions as follow-up monitoring and QA design into the actual remedial action plan.

3.2 Description of Evaluation Techniques

3.2.1 General

This section contains a survey of some of the techniques that are available for evaluating and comparing projects when one is to be selected from a number of competing options. This section is a synopsis of a discussion paper by Professor J. E. Dooley contained in Appendix II. The main purpose of this section is to give an overview of the evaluation techniques which may be of value in the optimization process for the choice of a decommissioning option for a uranium mill tailings site.

3.2.2 Cost-benefit Analysis

Cost-benefit analysis is best thought of as a concept rather than a technique. The concept is simply that, for any alternative, the costs and benefits are assembled. Then if the benefit exceeds the cost, the project has a positive value and becomes a candidate for adoption. In the case of the decommissioning of a uranium tailings site, the "benefit" can be seen as the reduction in the impacts of the site. The cost would be the cost im implementing a certain decommissioning option. A comprehensive hierarchy of criteria that lists the separate economic and social costs/impacts which may be considered in uranium tailings decommissioning is given in Figure 4.

The application of the cost-benefit analysis to the evaluation of the decommissioning options would involve the selection of measures that are suitable for expressing the costs and benefits. Many costs and benefits can be expressed directly in monetary units. This applies to capital and operating costs, and, possibly, to the value of the jobs created. The measurement of health impacts is usually in terms of the expected fatality risk. Most cost-benefit analyses of uranium fuel cycle projects are restricted to the use of only the project costs and the health impacts. The ICRP [4], however, has made an attempt to incorporate other impacts into the analysis. The natural units for measuring social costs are far from clear. For example, the measure of a criterion such as aesthetics is difficult and requires a large subjective input.

The next step would be the conversion of the different measures of cost and benefit to a common scale so that they can be aggregated and a net benefit or a benefit-cost ratio obtained. (In some cases there is no reasonable way to convert to a common scale and in such cases the costs or benefits may be considered separately). A common practice is to convert the various units for measuring costs and benefits to common monetary units using coefficients. For example, to convert fatality risk to dollars requires the dollar value of a human life. The linear multi-criteria utility technique discussed below is one way to convert to common units. Thus, in the case of aesthetics, the performance measure, say on a scale of 1 to 10 can be converted to a dollar value using an appropriate conversion coefficient. It is obvious that this procedure will be very subjective.

Finally, there must be some way of taking any important uncertainty into account. There may be uncertainty in the costs or the benefits. The uncertainty may be in where or when the risks will occur or the magnitude of the consequences. The probabilities of events with the different possible magnitudes of the consequences need to be estimated.

3.2.3 Cost-Effectiveness

Cost-effectiveness is a way of comparing the cost of an action with the benefit without having to convert to common units of measure. The technique generally is limited to comparing two factors at one time although different pairs can be compared separately.

Suppose, as an illustration that there are three decommissioning options A, B, and C under consideration. The benefit may be the reduction in radiation exposure compared with the "do nothing" option. The cost effectiveness of A is $2,500/man-rem reduction, of B is $3,750/man-rem, and of C is $5,000/man-rem. We can see that the marginal cost per man-rem reduction is increasing. This is apparent without the need to place a dollar value on a man-rem.

The example illustrates how cost-effectiveness, although not indicating the best alternative, does show how much extra it costs per unit of improvement in benefit. It is a matter of judgement, or policy or values, whether the extra benefit is worth the cost. The value of cost-effectiveness analysis is that it displays the trade-off inherent in the options very clearly. Cost-effectiveness can also be very useful for comparing the effectiveness of expenditures on competing activities in an allocation of resources problem.

3.2.4 Mathematical Programming

Mathematical programming techniques will find the mathematically best solution using only a single criterion and, of course, the solution is only "the best" within the assumptions and structure of the technique. Perhaps the best known of such techniques is linear programming. The assumptions are that "everything is linear". Linear programming uses a set of "decision variables" to represent the choices. In tailings disposal, for instance, the variables could be the amounts of money spent on each of a number of different options. The objective could be the reduction in man-rems of exposure . Linearity would be the assumption that, regardless of the amount spent on a particular project, there would be a constant rate of exposure reduction per unit of money spent on the project. Any number of constraints could also be imposed but these also need to be linear. The constraints could be limits on the total budget and other constraints providing they can be expressed as linear equations.

An example of linear programming is contained in Appendix II.

There are several extensions to linear programming that allow non- linear aspects to be represented. These form a more general class of techniques known as mathematical programming. To mention a few, we have: integer programming, dynamic programming, goal programming and non-linear optimization.

Non-linear optimization is the most general form of optimization technique. In non-linear optimization the linearity assumptions are relaxed for both the objective function and the constraints but it becomes much more difficult to deal with mathematically and computationally than linear programming and it is not always possible to find an optimal solution. Goal programming is a special formulation of linear programming in which there are several objective functions; one for each criterion. These are ranked by order of importance and the linear programming problems are solved using the objective functions successively starting with the most important. This is a very useful technique but cannot guarantee an optimal solution under all criteria. Dynamic programming allows non-linearity in the objective function but not interactions between variables. In integer programming the variables are integer and non-negative. Mixed integer programming allows a mixture of real and integer variables. This extension allows a lot more features of many decision problems to be included but at the expense of computational cost.

3.2.5 Decision and Utility Theory

Decision theory starts with a model of simple structure. The alternatives in this branch of decision science are usually called actions. The suitability of each action depends on which of a number of possible future events occurs and there is uncertainty about which future event will occur. The suitability of each action for each future event is measured by a "loss function".

The technique operates in two stages. One is to evaluate each action (expected value is one criterion) and the second is to choose an action on the basis of the evaluation. Typically, but not always, the action that has the lowest average cost (expected in the statistical sense) or highest average gain is the action chosen. Another approach is to choose the action that will minimize the maximum cost. In this case the evaluation of each action consists of finding the maximum cost if that action is chosen and the worst future event occurs for that action. Then the action is chosen that minimizes the maximum cost. This is similar to a strategy that seeks to minimize the worst case, regardless of how unlikely it is to occur. Utility theory extends the power of the decision theory technique.

This approach could be applied to the tailings disposal problem. The actions would be the decommissioning options. The future events, with uncertainty, could be the amount of contamination released. The loss function could express the number of cancers over some period of time for each option and each amount of release. The minimum expected value approach would find the expected cancers for each option and then pick the option with the minimum expected value.

3.2.6 Multi-criteria Utility Techniques

One of the most popular multi-criteria utility techniques is linear utility. In this technique the criteria are weighted in accordance with their relative importance. An option is considered under each criterion and a measure of its performance recorded. The option is evaluated by multiplying the performance measurement by the weight for each criterion separately and adding the products. This is very appealing because it produces a single number as an evaluation for each option. To apply the method we have to: find adequate measures of performance and evaluate the performance of each option under each criterion, and determine what weights to use. The linear utility technique also assumes that low performance under one criterion can be compensated for by an offsetting high performance under another criterion. Because of this trade-off feature, linear utility is one of a larger class of multi-criteria techniques known as compensatory techniques.

In the linear technique the trade-offs are made between equal intervals of the weighted performance. For instance, suppose the performance of an option under one criterion is 5, with weight 0.3 and under another is 7 with weight 0.1. The linear utility of this option, ignoring other criteria, would be 2.2. A second option with a performance of 4 under the first and 10 under the second would also have a linear utility of 2.2. We have traded off one unit of performance under the first for three units under the second because of the weights chosen.

A second form of compensation is to trade off ratios in what is called the multiplicative utility technique. In this case, using the above example, we would have (.3x5)(.1x7)= 1.05 as the multiplicative utility for the first option. To make the utility of the two options equal would require a performance of, say 4 under the first and k under the second criteria. To find k set (.3x4)(.1xk)=1.05 which gives k=8.75.

Another main class is non-compensatory in which trade-offs are not made but requirements are to be met under each criterion separately. There are several ways to apply the criteria which collectively create the class of non-compensatory techniques. Often the non-compensatory techniques are used to screen out options that are not acceptable and then other procedures are used to evaluate the remaining acceptable ones.

A third class of multi-criteria techniques are lexicographic techniques in which criteria are applied successively in a prescribed order and only until a clear winner emerges. In sporting competitions it is common to declare the winner of a division as the team with the most points on the season's play. If only one team has the most points, then the choice is made and no other criteria are used. If the top two, or more, are tied then the second criteria is used which might be tc declare the team that scored the most points as the top team. If this does not produce a clear winner the third criterion is applied and so on until a clear winner emerges.

3.2.6 Fuzzy Sets

Fuzzy sets have received a lot of attention recently as a way of making decisions when the problem is fairly unstructured. See, for example, Dubois and Rade [5]. In many decision situations it is difficult to obtain a numerical value for the probability of the consequences or a numerical measure for their cost or seriousness. It may, however be possible to get a verbal description such as a high, medium or low probability using a carefully constructed procedure. Likewise it may be easier to get a verbal description of the consequence such as serious, moderate or low. In fuzzy set theory these words would be mapped onto a scale of zero to one. If the probabilities are independent of the consequences then the evaluation of each option could be the minimum of the pair of mapped values for that alternative. The best alternative would be the alternative with the minimum evaluation since, in this case the consequence is unwanted so the least consequence is desired.

There is still a lot of controversy about whether this procedure adds anything that cannot be accommodated in decision theory or multi-criteria decision-making.

3.2.7 Global Judgement

Global judgement is an approach to decision-making in which an expert is given information about the options and makes a global judgement or choice from the options. An example from the medical field will illustrate the idea: a doctor is given a number of test results for a patient and makes a judgement about the patient's condition. In contrast the test results could be entered into a technique of some sort that would predict the patient's condition. In the decommissioning problem, global judgement would be equivalent to presenting the decision-maker with information about the technology and the site for each option. He would then judge one to be best without explicitly expressing, or even knowing, how the information was used or combined to make the choice. Terms such as "intuition", "gut-feel", or "experience" are commonly used to mean the same as global judgement. This approach is used in a surprisingly large number of situations and often successfully. The confidence in the result is typically dependent on the track record of the decision maker. In the absence of an appropriate technique or technique to combine the information into an evaluation and choice, this may be the only method available. The problem is that this method is difficult to justify to a public body or a group of peers.

3.2.8 Decision Systems

In Sections 3.2.2 to 3.2.7, several classes of techniques were discussed in terms of their structure, strengths, and limitations. It was stressed that all of these techniques provide a form of evaluation of the options but not the complete evaluation needed to make choices. They provide a useful input but that input must be combined with other factors to make a decision. A selection process that includes the evaluation and its combination with other factors, is a decision process or decision system. The flow diagram of the optimization process given in Figure 5 is an example of a decision system based on the tailings decommissioning problem.

A decision system may utilize several of the evaluation techniques discussed above for the evaluation of decommissioning options. For this reason, a decision system will be compared with the other techniques given above as a technique that is a hybrid of several individual techniques. An example of this is the use of a cost-effectiveness analysis for the health and cost impacts of the various options combined with the use of a multi-criteria analysis for the other impacts. The cost-effectiveness analysis would be performed first and the results of the multi-criteria analysis would be used to provide additional information for the selection of the best option.

Different techniques could also be used to screen out some options in the screening stage (see fig. 5).

3.2.9 Summary

A summary of some important features of the evaluation techniques described above is given in Table 1. These are the following:

- degree of structure
- number of variables
- the ability to handle uncertainty
- number of criteria
- transparency

The degree of structure of the technique refers to how rigidly the assumptions inherent in the technique constrain the flexibility of its use. For example, mathematical programming, which has a high degree of structure, is restricted in its application; whereas, cost-benefit analysis, which has a low degree of structure, has wide application.

The number of variables that the technique can accommodate represents the number of components describing the evaluation problem that can be interrelated conveniently by a mathematical expression or by other means.

The transparency of the technique refers to the ease with which the results can be seen to follow from the inputs.

The importance of any of these characteristics can only be decided in the context of a particular application. For instance, if the ability to take uncertainty into account is important then techniques such as linear programming are eliminated.

Table 1 Summary of Features of Evaluation Techniques

Method	Degree of Structure	Number of Variables	Includes Uncertainty	Criteria	Transparency
Cost-benefit	low	medium	not explicitly	several	high
Cost-effectiveness	low	few	no	two at a time	high
Mathematical Programming	high	many	no	one	low
Decision Theory	medium	few	yes	few	medium
Multi-Criteria	medium	few	no	several	medium
Fuzzy Set	medium	few	not explicitly	few	medium
Global Judgement	none	few	not explicitly	several	low to others
Decision System	variable	many	yes	several	high

TABLE 2 SUMMARY OF PAPERS REVIEWED

	Method				
Application	Cost Benefit	Cost Effect.	MAUT	Other	Total
Tailings	5	5	2	3	13
LLRW	3	1	4	5	8
HLRW	4	2	7	6	13
Haz. Waste	2	1	6	2	9
Mine Waste	-	-	-	-	-
Siting	-	-	14	6	14
Other Wastes	-	1	5	3	6
Other Applications	10	6	16	11	36
Total	16	19	62	46	

Note: Columns and rows do not necessarily sum correctly as some reports and articles contained more than one application and/or method.

Note: These numbers reflect only the relevant papers ultimately reviewed. See Appendix IV for more details.

3.3 Decision Techniques: Applications

3.3.1 Overview

Decision methods have been applied in a wide variety of diverse and varied fields. For the current project a literature search of these applications was undertaken for a limited number of pre-selected topic areas. The details of this search are discussed in Appendix IV and the findings are summarized in Table 2. Keywords were chosen in areas related to the uranium mine and mill tailings problem. These fields were searched explicitly and a detailed discussion of the various reports and articles are given in the following sections. Other areas or fields that have utilized evaluation processes, were also encountered in the literature. Since these were not extensively searched, these are only briefly mentioned in previous sections (3.2) and not detailed in the following sections. Only those that were specifically applied to the decision process are reviewed in the following section. Others, used to develop criteria values or papers descriptive of a method or tailings decommissioning alternatives were reviewed, entered into the annotated bibliography (Appendix IV) and discussed in the relevant sections of this report.

An overview of the papers searched and evaluated is given in Table IV-3 in Appendix IV. This table is organized alphabetically by author and summarizes the work done in the paper.

3.3.2 Uranium Mine and Mill Tailings

The literature on decision methods applied specifically to managing of uranium mine and milling wastes is not extensive. A number of general discussion articles and a few general applications of cost-effectiveness are available.

One of the most extensive applications of decision methods or systems arises from the Uranium Mill Tailings Remedial Action Project (UMTRAP) study on remedial action [6]. The decision system employed for this study involved the nonrecursive questionnaire polling of a panel of experts. The experts were asked, not only to rank and evaluate remedial alternatives, but also to establish the weights for the objectives. In the study two sites were evaluated (Salt Lake City, Utah and Shiprock, New Mexico). This procedure is a permutation of the multi-criteria methods discussed in the previous section.

The authors of the report performed extensive statistical analysis of the initial input data obtained from their questionnaire. They were surprised at the wide range in weightings. It was felt that this variation would be greatly reduced using a recursive technique. The authors concluded that the ranking of options would not have significantly changed with a reduced variation in the weightings. Only the confidence intervals of the final cardinal ranking of the alternatives would have changed.

The extensive statistical analysis of the input weights revealed that the variation in objective weightings could not be described by a normal distribution. Responses for the effectiveness of the alternatives and their effectivness rankings were found to be normally distributed.

Application of their method lead to the conclusion that for the two sites considered, earth cover was preferred over asphalt cover, moving the tailings to a new engineered pit or a thermal stabilization process.

The paper provides a readily applicable method for inclusion in a decision support system.

In May of 1983, Chee et al. [7] presented the results of a cost-effectiveness (cost and population dose) study for a uranium mill tailings site in Salt Lake City, Utah and a thorium processing facility in West Chicago, Illinois.

Three alternatives were considered for each site: onsite stabilization (including cover), offsite disposal and a no action alternative.

The results of the study showed that for the West Chicago site, the dose-reduction cost for on-site stabilization was about 20 times less than dose-reduction cost for offsite disposal. For the Salt Lake City site, this difference was approximately a factor of 10.

Their conclusions, in terms of preferred remedial action, did not change in their cost-effectivness calculations based on annual dose reduction or on a cumulative 200 year population dose.

In 1982, Osborne [8] and in 1983, Olivier, Osborne and Rafferty, [9] discussed the results of a OECD-NEA [10] study on the long-term management of uranium mill tailings. The study analyzed remedial actions using a cost-effectiveness approach. Three hypothetical reference sites (semi-arid, tropical and northern temperate) were considered.

The authors focused on the collective effective dose equivalent commitment as the basis for performing their optimization. An upper limit of 10,000 years was considered. It was felt by the authors that "differences in radiological protection attained by different ways of managing the tailings would be masked by uncertainties in predicting the performance of engineered structures in the far future, and also by uncertainties in the dispersal and distribution of radionuclides". The authors also noted that different optimal solutions were possible depending on the time used to integrate the collective dose.

The authors criticised the direct application of a cost-benefit approach as being incapable of directly accounting for hazards from other contaminants. Other social and economic factors could also not be readily taken into account. Their conclusions stated "that the cost-benefit approach to optimising radiation protection can only provide limited inputs to decisions on tailings management."[10]

The results of their evaluation for a generic northern temperate tailings site, indicated that the construction of impermeable dams was the most cost-effective approach for the remedial actions considered.

In 1985, Paschoa et al [11], presented the results of a very specific aspect of uranium tailings, namely the optimization (cost-effectiveness) of cover depths. Their procedure involved a direct application of radon flux attenuation modelling compared to normalized equations considering the differences in cost with various depths of cover. Dose was not considered.

The authors concluded that for a very limited application, the cost-effectiveness analysis approach could be used advantageously. They felt that one of the main strengths of applying this technique to a specific application avoided all of the pit falls of dose estimation and determining a dollar value for collective dose.

Van Dyke, in 1983 [12], produced a report for the U.S. Department of Energy, concerning the application of cost-benefit analysis to long-term isolation of uranium mill tailings. In this report, Van Dyke identifies the time frame that must be considered as one of the most fundamental and important criteria in determining the cost-benefit ratio.

The author concludes that not only does the application of a classical cost-benefit analysis to uranium tailings involve the usual problems of a C-B analysis, but the need to consider an extremely long time horizon adds a fundamental ethical and moral judgement. Classical time discounting was not considered to be justified for long-term, intergenerational effects.

Van Dyke illustrated this discussion with a cost-benefit analysis applied to the setting of radon flux standards. From the moral and ethical point of view, the decision of regulated flux level should be set at either zero or at a level where the marginal costs of reducing radon are equated to the undiscounted benefits across all generations. The optimal action level was then established based on the authors' assumed value of a human life.

3.3.3 Low Level Radioactive Waste

In 1985, Short [13] reported a summary of the results of his masters thesis on a cost-benefit analysis to compare the alternatives of shallow land burial and greater confinement for the disposal of low level radioactive waste.

The paper details the development of the costs associated with the disposal alternatives, including various waste volume reduction options. The "risk" of each alternative was obtained by summing the doses to individuals (intruders were included) to a distance of 80 km. The dose was converted to a cost on the basis of $1,800 per person-rem. Other criteria were not considered.

Standard cost-benefit ratios were calculated and a sensitivity analysis was performed on the input parameters. Results were reported as the best alternative for different low level radioactive waste generators (eg. hospitals, power stations). Neither the results or ultimate use of the sensitivity analysis were discussed in this paper.

Hart [14] uses a very simple weighting matrix to evaluate various alternative sites for the disposal of radium wastes found in Denver, Colorado. Weights, totaling one hundred, were assigned to each of the 13 evaluation criteria (cost, public acceptance, lead time etc). Performance under each of these criteria were then evaluated and ranked. Sum totals of the weight multiplied by the performance under each criteria, resulted in final scores for each alternatives.

3.3.4 High Level Radioactive Waste

In 1983, Sioshansi [15] authored a paper concerning the use of an expert judgement system to evaluate alternate plug designs for deep geological high level radioactive waste disposal sites. The evaluation was based on polling individual experts in various relevant areas of knowledge (geotechnical, material behaviour, geochemistry etc) and deriving a "collective" result.

The use of a Delphi technique (roundtable expert discussion until a consensus is reached) was rejected by the author on the basis that pressure is exerted within the group to arrive at a consensus. In most decision studies of this nature, the strengths and weaknesses inherent with different alternatives should be specified. This was not possible with the Delphi technique. With their current technique, responses were obtained independently.

The technique by Sioshansi involved the development of a comprehensive questionnaire, which required each evaluator to focus on specific aspects of the problem (ie. criteria). Ratings were performed on a four point scale (A to D) and evaluators where requested to provide a brief explanation of their evaluation. Though the questionnaire could be self administered, the current study used interviews to lead the evaluators through the questionnaire. For the 17 plug schemes suggested 15 questions were used. The total interviewing time was approximately eight hours per evaluator.

The results of the questionnaires were reduced by using a minimax principle. Due to the nature of the decision system employed in this study, not only were the "best" (ie acceptable to all fields of expertise) alternatives identified, but areas where improvements in design were possible and the rationale for low ratings could be identified.

In 1977, Otway and Edwards [16], applied a multiattribute rating technique to the evaluation and consideration of nuclear waste sites. The primary purpose of their work was to demonstrate multiattribute analysis and evaluate a number of alternative methods. As a result, criteria values were informally collected and were used for illustrative purposes only. On the other hand, the respondents requested to partake in the study were experts in the field.

The authors quickly rejected some of the more elegant techniques based on indifference gambles. (i.e. at what point were the decision makers indifferent to the difference between the performance under two criteria) The experts polled were concerned about the abstractness and lack of realism introduced in the hypothetical indifference gambles.

Mean values for the weights were used to calculate the utility value for each alternative.

The authors recommend that in cases where there are major differences in either the assigned weights or criteria values for the alternative, that the experts be contacted to further understand or even re-evaluate their initial decisions. The authors did not have the opportunity to take this step during their study.

The authors concluded that their method was successful in determining a defensible ranking of the hypothetical sites.

Vuori et al [17] studied the use of a cost-effectivness evaluation for high level radioactive waste management options in Finland. This approach was taken, as opposed to a cost-benefit evaluation, to avoid the necessity of assigning a monetary value to exposure levels.

The authors concluded that in performing an analysis on the basis of individual dose rates, a probabilistic approach is desirable. Ranking of alternatives on the basis of collective dose gave the same ordering as for individual doses. This was not dependent upon the integration time used. Increasing the integration time decreased the differences in collective dose committment between options. The authors recommended the use of a limited time interval around the time of highest exposure as an appropriate option.

Comparisons to natural background and life expectancy calculations also gave the same ranking of alternatives, but were considered to give an extra benefit of placing the alternatives in perspective with other risks in society.

Kirkwood and Sarin 18 use a method of ranking multiattribute alternatives based on only partial information about the weighting. The method was found to be useful, not as a method of obtaining an optimal solution, but as a method of obtaining a set of alternatives requiring further investigation. The authors applied their technique to the choice of materials for borehole and shaft plugging in a high level waste repository. The developed method is relatively simple to apply and requires only a pair wise rating between the alternatives (ie. alternatives are compared in pairs). Actual weighting of the criteria was not required, only a ranking of the importance of the criteria was necessary.

In 1982, Lathrop and Watson 19 used a decision system to differentiate between two high level waste repository sites. The method used by the authors was an extension of standard Multiattribute utility theory (MAUT) with an additive utility function.

The authors considered future effects as a separate criteria and did not attempt to discount or otherwise combine these effects with more current effects. In so doing, each decision maker was free to weight the future effects in what ever manner they considered reasonable.

Weighting values and utility functions were obtained by one hour interviews with each interested party. These values were then combined to obtain a group utility function by the use of equal weighting of calibrated utility functions.

In 1983, Salmon 20 used a decision system to choose between radioactive waste management options. The author realized the importance of considering numerous attributes in the decision process. The author developed a method whereby a limited number of alternatives were ranked on the basis of performance under each criteria. The decision makers were then required to assign a weight to the various criteria. The stakeholders are then required to rank the options on the basis of their ranking under the criteria and their assigned importance to that criteria. In the real waste management case presented in the paper, the authors found that the same alternative was chosen by each group of stakeholders, though for different reasons. The authors note that the main benefit of their method is the structuring and clarification of the discussion. The authors did not comment or suggest methods of handling a situation where the stakeholders did not reach the same conclusions.

3.3.5 Hazardous Waste

In 1985, Horsak and Damico [21,22], presented a paper concerning the use of fuzzy set analysis in the selection and evaluation of hazardous waste disposal sites. This study relies on the Yager [23] procedure to evaluate the weightings of the various criteria.

Yager determines the relative importance of one criterion over another through the use of paired sets of criteria. In Horsak and Damico's study, the final ranking of the hypothetical sites is based on the lowest weighted value for each site (ie. best alternative has the highest minimum weighted criteria value).

Few details of the actual calculation procedure are supplied by the authors but a simple example allows the procedure to be readily derived. The questionnaire used for determining their paired comparisons of the 10 criteria used for their hypothetical disposal sites is given.

Shih and Ess [24] suggest the use of a multiattribute decision process in conjunction with a risk assessment for evaluating clean up alternatives at an uncontrolled chemical dump site.

The authors use a procedure based on the work of Rowe [25] to reject alternatives in the initial list of options by comparing objective risks (calculated risks for the alternative) with referent risks. This procedure, used with the risk assessment, compares risks across the entire spectrum (ie. involuntary catastrophic fatal risk through regulated voluntary, ordinary health risks). This procedure reduced the possible clean up alternatives to two from an initial set of 6 alternatives. These two were compared using a multiattribute utility analysis. Individual utility functions were generated and an additive multiattribute utility function was used to compare the remaining two options.

The work of St. Clair and Sherman [26] presents a relatively simple and elegant cost-effectivness approach that allows the consideration of many non-specific (subjective) criteria.

The method used by the authors, consists of assigning weights to the criteria, rating each alternative for each criteria and eventually summing the weighted ratings. The cost effectiveness of the alternative is calculated by dividing the effectiveness rating by the sum of the costs. This is considered to be a "cost effectiveness score" for the alternative. The best alternative has the highest score.

The authors claim that even though this is not a mathematically rigorous approach, it is a useful in supporting decision about remedial actions. Its ease of use and its relative simplicity allow it to be readily understood by non-technical persons. In addition the method allows a quick sensitivity analysis to confirm the final rankings. The authors recommend a Delphi approach to eliminate outliers in the weighting or rating development phase of the analysis.

In 1986, Jennings and Suresh [27], presented a comprehensive paper on the application of fuzzy set analysis to hazardous waste management options.

The work relies heavily on a computer algorithm to solve the fuzzy set matrix and obtain a ranking of alternatives on the basis of risk. The authors feel that the ability to use these algorithms interactively on a computer system is a very strong benefit of this approach. All interested parties, involved in the decision process, could then use this method to rapidly evaluate their options. The authors are quick to point out that their approach is only useful in the early stages of a decision process, at a point where the decision makers are trying to form their preferences and potential tradeoffs.

Shecter, in 1985 [28] uses a cost-effectiveness approach to study various groundwater protection and management policies near the Price Landfill site in New Jersey. The study focused heavily on the development of the risk estimates from ingestion of the contaminated groundwater. The author uses the range of risk estimates to develop a range of cost-effectiveness for each option. It was noted that the great variation in results came from the great variability in the risk estimates. No consideration was given to intergenerational effects.

3.3.6 Other Mine Wastes

No relevant literature was identified during our search concerning the decommissioning of mine wastes, other than that for uranium tailings discussed in Section 3.3.2.

3.3.7 Siting - Nuclear Power Plants

The literature abounds with the application of multiattribute utility theory (MAUT) techniques for the siting of nuclear power plants. The literature is dominated by the work of Keeney (see, for example all references under Keeney, [29-38] and Kirkwood [39]), who pioneered much of the development of MAUT. A description of the method is not warranted in this discussion. Numerous approaches and permutations on MAUT are found in the literature. These are almost as abundant as the number of papers dealing with MAUT. Only those aspects in the various studies that are relevant or of interest to the current study will be highlighted.

Others, such as Church and Thomas [40], have developed methods for baseline screening of candidate areas. Though these are formal decision processes, the methodologies are too specific to the screening problem to be useful for optimising tailings management options. As a result, these papers are not reviewed in this report.

Solomon and Haynes [41] present a detailed critique of multicriteria decision methods applied to nuclear power plant siting. Their work draws upon an extensive review of 48 real site selection studies and an overview of the methods used in these studies provided by Brookhaven National Laboratory [42].

The authors give a detailed discussion of the rationale behind the use of multiattribute systems. They contend that one of the principal uses of all decision systems is the ability to provide the decision makers with information at different stages of the project. They conclude that there is no single multidimensional algorithm or model suitable to power plant siting. The nature of the problem and even the characteristics of the sites will dictate the optimization procedure. The authors also conclude that all of these methods are decision aids, not replacements for the decision process.

One of the more critical steps in performing a MAUT analysis, is the determination of attribute weighting. In 1980, Hobbs [43] considered a number of weighting methods and evaluated them in the context of nuclear power plant site selection in the western Maryland area. Of specific interest, is the studies use of weights derived from trade-offs versus weights derived from a ranking scale (not a ratio scale!) of 0 to 10. These two methods were used to evaluate the results of a regional screening study for candidate sites.

The authors found that there were significant changes in the chosen areas between the two weighting techniques studied. Overlap of the chosen areas was only 52%. They concluded that in order for a weighting technique to be valid, weights must be on a ratio scale.

In an interesting study by Ford, Keeney and Kirkwood [44], a number of evaluation or decision systems were considered for their applicability to the nuclear power plant siting problem. In effect, the authors perform a multi criteria evaluation of the various evaluation methods.

The results revealed that comparison screening (MAUT) was superior to the other methods for site selection. All of the methods, as applied in the reference studies, were considered to be poor in their ability to handle public input, multiple concerns, uncertainties and long term impacts.

In 1982, Abdul-Fattah and Abulfaraj [45], used a fuzzy set method to choose between two potential nuclear power plant sites in Saudi Arabia.

It was recommended by the authors that fuzzy set be applied in a similar fashion to a normal MAUT process. The application of fuzzy set theory, in this fashion, eliminates the requirement that the decision maker must assign specific numerical values and uncertainties. For the purposes of their study, the authors used a simpler ranking system. Rating and ranking were done on the basis of verbal description, rather than specific numbers. The authors used the MAFDA computer program, developed by Watson et al. [46], to calculate their final preference.

This method was successful in differentiating between the two sites.

3.3.8 Other Waste Handling

Multiattribute utility theory was used by Collins and Glysson [47] to decide between two different municipal waste disposal options. There were no deviations from the standard MAUT methods used in the literature.

The authors used a Delphi technique to obtain the utility and weighting functions. Two evaluators, familiar with the field of solid waste disposal were used as the decision makers.

The authors point out that one of the strengths of this decision process rests on the ability to focus future effort towards areas that are identified as critical or significant and not waste effort on studying the details of criteria that do not effect the final decision.

In a study on sewage sludge disposal options for the Boston area, Perlack and Willes [48], utilized a linear programming model.

In 1981, Sobral et al.[49] applied a multi criteria procedure, based on fuzzy set analysis, to the evaluation of solid waste disposal alternatives in the Regional Municipality of Waterloo, Ontario, Canada.

Cost-benefit analysis were rejected by the study team due to its inability to handle environmental and social impacts that could not be measured in monetary units.

During this study, each interest group was requested to evaluate the alternatives and assign weights to the criteria. The Delphi technique was used within each group to arrive a consensus.

Various methods of aggregating these matrices were considered (mean, weighted mean, maximum, etc) to produce one solution matrix of criteria and alternatives. The mean and a modified pessimistic (average of the mean and pessimistic matrices) approach were used for the Waterloo study.

A multi-criteria evaluation (MCE) technique (a permutation of MAUT) was used by Maimone [50] to compare solid waste treatment and disposal options in the Netherlands. The method utilizes the concept of alternative dominance (ie. pair wise comparison) to generate a dominance matrix. Both ordinal and cardinal rankings are used in the evaluation. This is followed by the application of criteria weights to determine the overall dominance matrix. Appraisal scores are then additively generated for each alternative. The matrix concept allows the decision maker to consider each alternative on the basis of the appraisal score, but also for the strengths and weaknesses under each criteria.

3.4 Comparison of Evaluation Techniques

In order to determine the suitability of the evaluation techniques described in section 3.2 for evaluating decommissioning options, the techniques will be compared with respect to a number of factors that concern their application (described in section 3.4.1). The comparison of the various techniques for use in the tailings decommissioning optimization process is described in section 3.4.2.

3.4.1 Factors for Comparing Evaluation Techniques

The following factors are applicable for comparing evaluation techniques for any particular application including the tailings decommissioning problem.

A. Benefit/effort considerations

In general, more aspects of the real problem represented by the technique can be included by making the technique more sophisticated. This can increase the benefit of using the technique for decision-making purposes, but this is at the expense of increasing the amount of data, often the amount of computations, and time to structure the technique and interpret the output. All of these increase the effort and cost. Thus there is a balance between the effort required to use the technique and the benefit derived. The marginal benefit will often decrease with increasing sophistication and the marginal effort will increase.

B. Representation

In any application there are aspects of the real world that have to be incorporated into the decision and, if possible, into the technique. The "representation" factor is the degree to which the technique incorporates the important features of the problem. In some cases important features can be considered outside of the technique using the technique to represent only those features it can incorporate readily. For instance, it may be possible to incorporate uncertainty by including a separate criterion that reflects the uncertainty of health impacts.

C. Credibility

Credibility refers to the degree to which the stakeholders understand and believe in the use of the technique for the decision problem. Lack of credibility may come about because they do not understand the structure of the technique and so have no faith that it is representing the problem as they want it represented.

D. Acceptability

The technique should be acceptable both to the stakeholders inside the organization doing the evaluation and to people and organizations that are stakeholders but are outside of the organization performing the evaluation. To do this, the technique must incorporate considerations and criteria that the stakeholders consider as being important, and must do this in a way that enables comparison with the decisions of other organizations. For instance, the decision on decommissioning must be made using techniques acceptable to the requirements of the organization doing the analysis. Also the technique has to be acceptable to the AECB, the scientific community and the public. To some degree the more explicit the technique is the more acceptable it is.

E. Transparency

It is assumed that techniques provide an analysis of selected parts of the decision problem which is then combined with other factors in an optimization process. Thus the technique should be able to make a suitable contribution to the system by making the assumptions transparent, and supplying useful information that can be seen in relation to other factors not in the technique.

F. Skills required

This factor refers to the need to have the skills to use the technique effectively. This is an increasingly important factor as computer software enables the computational aspects of techniques to be accomplished easily without having to understand the techniques. However, if the technique is not understood, then the computed results cannot be used effectively. Moreover, it is assumed that the decision is not made based on computed results alone.

G. Data requirements

Data requirements is a factor that should be considered in technique selection to be sure that the necessary data can be obtained with adequate accuracy. Some of the techniques require objective data that is the result of extensive analysis, eg pathways analysis to obtain values of dose for use in a cost-effectiveness analysis. Other techniques, such as multi-criteria analysis are designed to handle problems in which a broad range of data from objective to very subjective can be considered.

H. Experience with the Technique

Experience with a given evaluation technique can be important for a number of reasons. These include; greater confidence in the method, more extensive supporting literature and the availability of data in the forms required for the technique.

3.4.2 Feasible Evaluation Techniques

The discussion in this chapter has described a number of general classes of evaluation techniques, their characteristics and examples of their application in similar decision problems. Some of these methods are appropriate for the tailings decommissioning problem, but a number of them are not. The features of the various evaluation techniques were described in Table 1. A comparison of the evaluation techniques, as applied to the decommissioning problem, with respect to the factors discussed in section 3.4.1 is given in Table 3. The following discussion is specific to the tailings decommissioning optimization process.

One of the requirements discussed in previous sections dealt with the data handling capabilities of the decision technique. This could not readily be evaluated for the general problem of tailings decommissioning, as for most of these techniques it is dependent upon the level of effort and ultimate requirements of the technique. For example, in global judgement only one criteria can be used (for example health risk by environmental groups), but more criteria or data might be used by the responsible company executive. For the other techniques, it is possible, with increasing effort, to incorporate a large amount of data. The amount of data or number of relevant criteria which will be used in the evaluation process must be established as part of the ground rules in a decommissioning problem. Once established, most of these techniques can be used to handle the relevant data.

The benefit/effort for the various techniques, is highly variable when applied to the tailings decommissioning problem. A cost/benefit or cost/effectiveness analysis, is relatively easy to apply to health and cost impacts. When these techniques are extended to other impacts, the effort required to perform the analysis increases dramatically without a parallel increase in results. Many of the other evaluation techniques require quite extensive effort but result in increased information for the decision maker. Mathematical programming, when compared against the benefit/effort of other techniques, has a very low rating. Extensive effort is required not only to

TABLE 3 COMPARISON OF EVALUATION TECHNIQUES

EVALUATION METHOD	Benefit/ Effort	Representation	Credibility	Acceptability	Transparency	Skills Required	Experience with related problems
Cost-Benefit	high	good	medium	medium	high	low	extensive
Cost-Effectiveness	high	restricted	medium	high	high	low	extensive
Mathematical Programming	low	restricted	low	low	low	high	limited
Decision Theory	medium	restricted	medium	medium	medium	medium	limited
Multi-Criteria (add.lin.utility)	medium	good	high	high	medium	medium	extensive
Fuzzy Set	medium	good	medium	unknown	medium	medium	some
Global Judgement	low	good	low	low	low	high (expert)	extensive
Decision System	high	excellent	high	high	high	medium	unknown

set up the necessary input data, but also to develop the equations and conditions required for the analysis. The result of such an analysis does not warrant the required effort.

The second evaluation factor, representation, is good for general techniques such as cost-benefit, decision systems, multi-criteria analysis, and global judgement, but is generally restricted for cost-effectiveness analysis, mathematical programming and decision theory.

For the first two techniques, it is necessary to aggregate a number of widely different criteria by one or two common denominators (for example, dollars or dose). This often leads to very controversial input data (eg. aesthetics measured in dollars). To perform this task in a manner reflecting the real world, is often very difficult. The other techniques can represent the actual tailings decommissioning problem by a more realistic set of criteria.

For the majority of the evaluation techniques, the credibility is quite high. Global judgement is very dependent upon the credibility of the decision maker. In a highly publicized decision process, such as the tailings decommissioning problem, there will be numerous "experts" all with varying degrees of expertise and most likely all with different "optimal" solutions. Mathematical programming is considered to be low in this application since, because of its complexity, most of the stakeholders would not understand the details of the analysis. On the other hand, a decision systems technique, has very high credibility since avenues are available for all stakeholders to voice opinions and examine information and have input into the decision process.

Acceptability, both internal (ie. to the mining company) and external (ie. to the AECB and public), is highly variable between techniques. A number of the more general aspects of these techniques, such as the problem of assigning a dollar value to human life, have been discussed under the various technique descriptions. It is not currently possible to evaluate the internal acceptability of the various techniques for tailings decommissioning. Historically, the uranium mining industry has tended towards the use of cost-benefit or cost-effectiveness and the nuclear power industry has oriented towards multiattribute utility analysis to solve siting problems. The external acceptability of these techniques is also highly variable. Even though many decisions are based on global judgement, in a public forum or in terms of approvals acceptability, this technique has a very low rating. On the other hand, both the public and the regulatory authorities have been frequently exposed to techniques such as decision systems, multiattribute utility analysis and cost-effectiveness and therefore are more likely to accept them.

The transparency of the technique is also important in its application to tailings decommissioning. It is important that others, not involved in the actual evaluation technique, can understand the technique and the results of the technique. To this end, this requirement also assists in determining if a specific technique is useful in a decision system. Since the tailings decommissioning problem is an issue fraught with much publicity and many stakeholders, it is important for any chosen technique to be clearly understood. Although many of the evaluation techniques are highly transparent, techniques such as global judgement and mathematical programming have low transparency. It may be difficult to readily see how the other impact factors criteria are utilized in a multi-criteria analysis and fuzzy set analysis.

Decision techniques vary greatly in the skills required to apply them to the tailings decommissioning problem. In the case of global judgement (assuming an expert) and mathematical programming, a very high level of skill is required. For other techniques, the methodology is relatively straight forward and can be applied with some training or guidance.

Experience with the techniques, as used in related problems was extensively discussed in Section 3.3. Most of these techniques have been applied in related problems. A summary is shown on Table 3.

On the basis of the above comparison of the evaluation techniques, feasible techniques for the optimization of the tailings decommissioning problem are a cost/benefit analysis, a cost/effectiveness analysis, a multiple attribute linear utility analysis, and any or all of these incorporated into a decision system. These have all been used in similar or related problems (see Section 3.3). Some of the variations on these techniques were discussed in the previous sections (methods of weighting criteria, methods of obtaining values etc). The methods applied to the example problem in chapter 5 will be based on the most suitable of the literature variations. Where useful, other variations of the techniques will be discussed.

Other techniques, such as global judgement and mathematical programming, are not as suitable to the tailings decommissioning problem. These techniques are deficient in their performance under one or more of the evaluation technique requirements discussed above.

4.0 PERFORMANCE OF THE VARIOUS OPTIONS UNDER THE CRITERIA

4.1 Introduction

The following chapters provide a demonstration of how to apply the optimization process to the tailings decommissioning problem. In this particular demonstration, the various evaluation techniques selected in section 3.4 will be applied. Since these techniques include multi-criteria techniques, the performance of the options with respect to all of the criteria given in figure 4 will be estimated. This corresponds to step F of the optimization process shown in figure 5. In an actual problem, the step immediately preceding would have indicated the significant criteria and the likely evaluation techniques to be used (step E). Step A to step D involved the choice and description of the feasible tailings decommissioning options as discussed in Section 2.2. The reference site for this study is described in Section 2.1

In this demonstration, the numerical values of the performance of the options under the criteria were based on readily available data. They were chosen to be representative of possible values in a realistic evaluation; however, because of lack of specific data many assumptions and many subjective values were necessary. In the discussion that follows, it will be indicated which data is generally objective and which is subjective. The performance results of the various considered options are discussed in the following sections.

4.2 Health Impact Criteria

Quantitative data are generally readily available for the determination of the performance of the various decommissioning options under the health impact data. This is generally available from pathways analysis, worker dose calculations, and a general risk analysis for each of the options. In some cases, such as the one described in this example, the pathways analysis may be performed using a probabilistic model and thus a measure of the uncertainty of the various health impacts would also be available.

The effect of the various decommissioning options described in the present example on the health impacts are given below.

Option 1: The base case option is the walk-away scenario in which the contaminant releases from the tailings area are basically the same as during operations if the treatment plant were removed. The individual doses assumed were those calculated in a 1987 report by SENES[51]. Collective doses were assumed to result from the drinking water and fish pathways only. The local population used the water and fish of lake 2 and the regional population used that of lake 3 (see figure 6). It was assumed that a dam failure following a large precipitation event would constitute an extreme event and that the consequences would be those given in a 1986 NUTP report[52] (10% of tailings mass transported to first lake). The probability of this event is 5×10^{-5}/a.

There were no occupational doses assumed for this option as no further work was required at the site.

Arsenic and nickel are not normally present in significant pore-water concentrations in eastern tailings. In western tailings, however, arsenic is present in concentrations of about 7 mg/L and nickel in concentrations of about 1 mg/L. Although completely unrealistic for the properties of the reference tailings site; the presence of arsenic and nickel was included to demonstrate how non-radiological contaminants would be considered by the evaluation techniques. The concentrations of arsenic and nickel were assumed to be 20 times less than those at a reference western site (the factor by which the radium concentration is smaller than at the western site [3].)

The assumed porewater concentrations of arsenic and nickel in the tailings were 0.35 mg/L and 0.05 mg/L, respectively.

REFERENCE SITE OVERVIEW

(from Ref. 1)

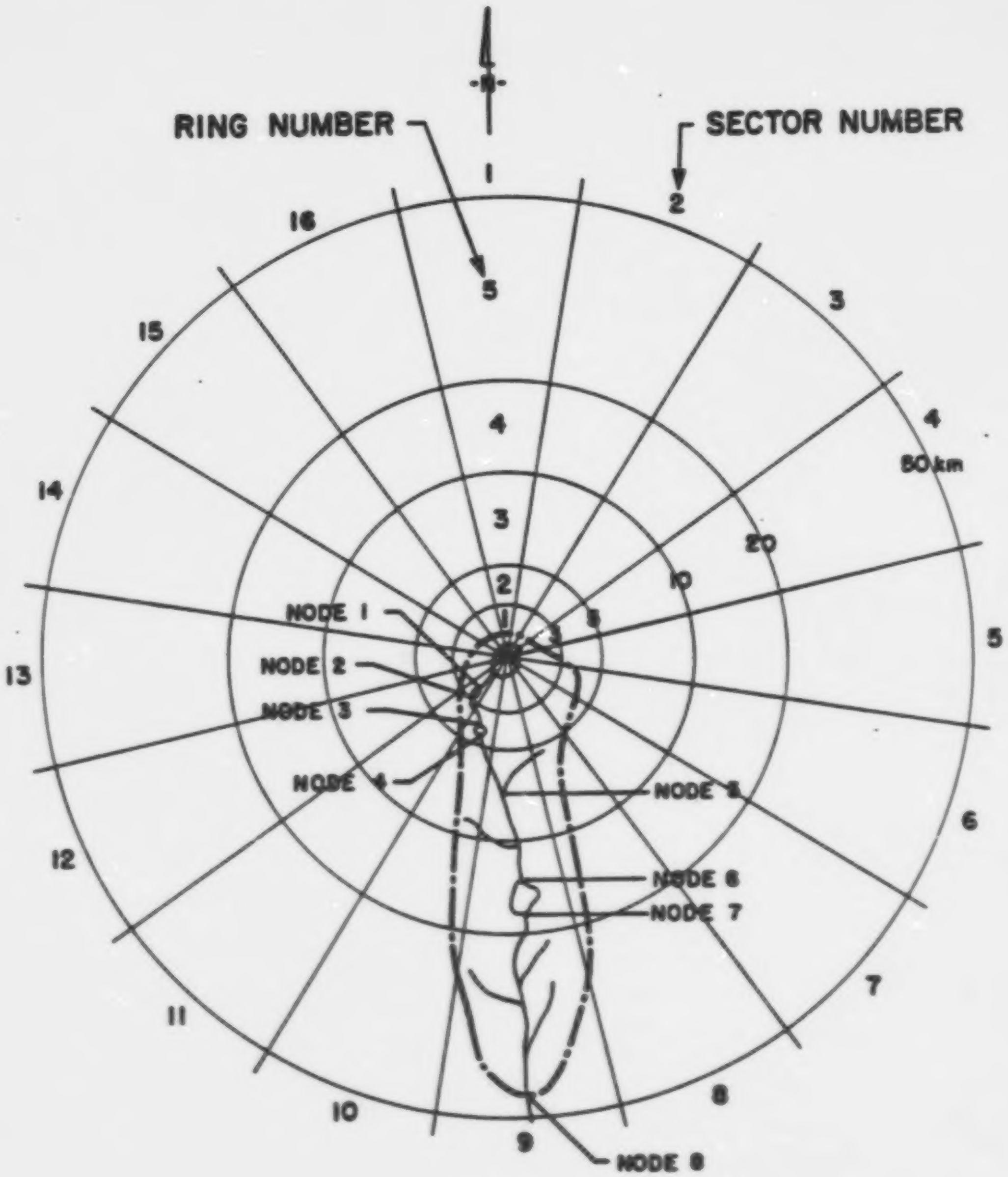

N
RING NUMBER
SECTOR NUMBER
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
5
4
3
2
1
50 km
20
10
5
NODE 1
NODE 2
NODE 3
NODE 4
NODE 5
NODE 6
NODE 7
NODE 8

FIGURE 6

The reduction in concentration due to sedimentation and dilution of the released contaminants was assumed to be 50 times at lake 1, 100 times at lake 2, and 400 times at lake 3.

Option 2: The pyrite reduction and limestone addition option changes the release characteristics of the tailings; however, this scenario is similar to the base case in all other ways. The individual doses were those calculated in a 1986 NUTP report[1]. The collective and extreme event considerations were the same as those for the base case. Occupational dose was only accumulated during limestone addition.

Option 3: The vegetation option was assumed to be basically the same as the base case except that evapotranspiration on the tailings was assumed to be increased initially. Thus the amount of water percolating through the tailings and contributing to the water pathways would be decreased (assumed one-half that of the base case). Collective and extreme event considerations were assumed to be the same as the base case. Occupational dose was accumulated during the surface reshaping and the limestone addition and vegetation.

Option 4: Covered Tailings would virtually eliminate the radon pathway, eliminate the airborne particulate pathway and are assumed to reduce the water pathway releases to 20% of the base case. Collective doses were calculated using the same considerations as for the base case. In the case of the extreme event, only 5% of the tailings material was assumed to be transported to the first lake.

Occupational dose would be accumulated during the dewatering, shaping and covering of the tailings. A study on decommissioning options by MacLaren Plansearch Inc. in 1984[53] was used to estimate the occupational doses.

Option 5: The addition of the grout curtain in the dam as well as the three meter cover basically ensured that the only releases to the water system would be through the groundwater system. As in option 4, the releases to the water system were assumed to be 20% of the base case. This option also involves a retardation of contaminants as they are transported through the groundwater system and thus the behaviour of the health impact with time is different from that in the first four options. Collective dose considerations were the same as the base case. In the case of the extreme event, it is assumed that only 1% of the tailings material was transported to the first lake.

Occupational dose was assumed to be the same as that calculated in option 4.

Option 6: Relocation of the tailings to a remote basin would result in releases similar to those in option 5; however, the healths impacts would be considerably less because of the remoteness of the site from significant surface water bodies. In this case, the retardation of the contaminants could be considerably longer than that in case 5. All other considerations would be the same except for the occupational dose calculation. The excavation, transport and placement of the tailings must be taken into consideration. The MacLaren report[53] was used to estimate these doses.

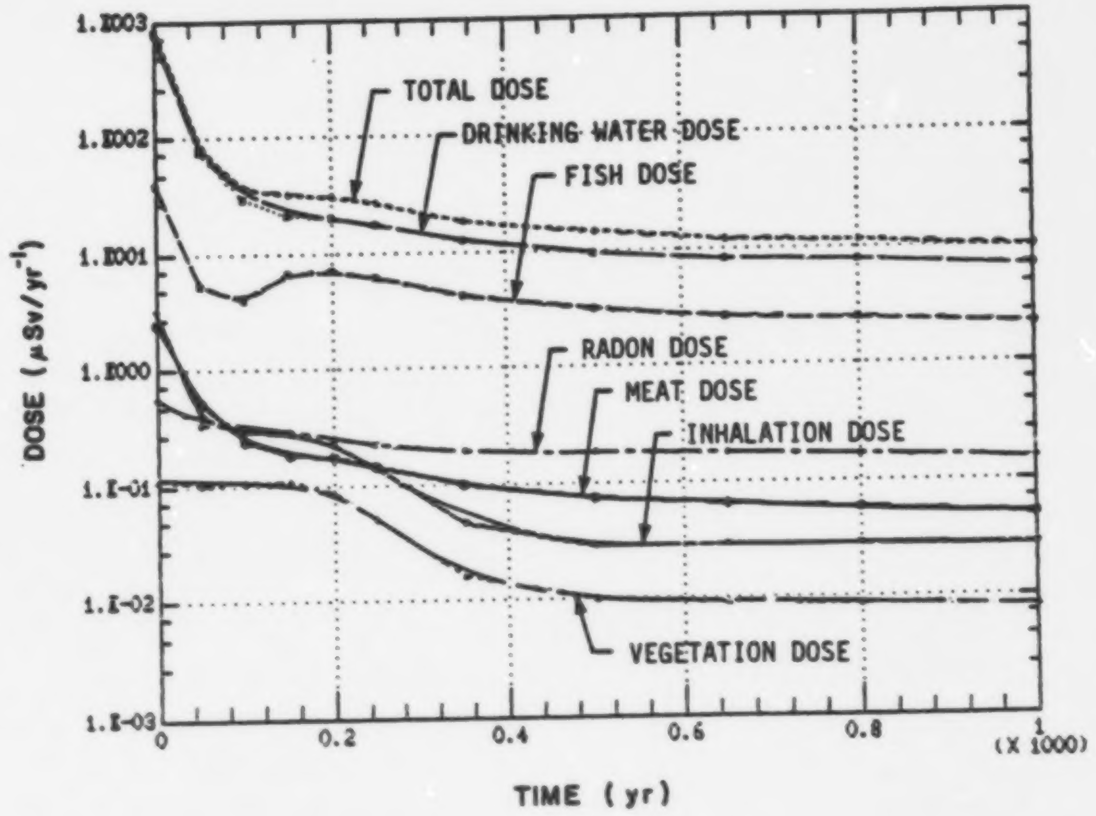
Option 7: The perpetual treatment option assumes that both the decant water and the water seeping through the dam are treated to meet water quality standards prior to discharge into the river. The extreme event scenario was the same as that in the base case.

In order to estimate the health impacts for the various options, the individual doses calculated for the base case in the SENES report[51] were used and prorated according to the decrease in the release rate to the various pathways. Arsenic and nickel concentrations and uptakes were estimated from results in a 1986 NUTP report[3] by comparing release rates of the contaminants from the tailings pond and dilution rates in the surface water bodies.

The results in another 1986 NUTP report[1] indicated the drinking water pathway (figure 7) was the major contributor to the dose (>75%) and the fish pathway accounts for most of the remaining dose at 250 years. At year 0, the drinking water pathway accounts for more than 90% of the dose. At year 250,

DOSE vs. TIME BY PATHWAY
(SCENARIO I)

(from Ref. 1)



NOTE:

GEOMETRIC MEAN VALUES OF 200 TRIALS

FIGURE 7

Ra-226 is the major contributor to the drinking water dose (figure 8); whereas, at year 0, lead and thorium are the major contributors. The thorium contribution decreases below that from radium within 50 years and the lead contribution decreases below that from radium within 150 years.

To illustrate the use of the selected techniques only the drinking water dose was considered. The effect of the various options on the drinking water dose is estimated by assuming that the doses for the various options are directly proportional to the changes in release rate of the various options relative to the base case in options two to five and option 7. Only an upper bound could be estimated for option 6.

Table 4 summarizes the results of the base case analysis. In Table 4, the radiological impacts are given at 0, 250 (time of peak), and 1000 years (maximum analysis time). The arsenic and nickel results are given only at 250 years. In the case of arsenic and nickel, the impact is constant as a function of time for all options except options 5 and 6. In these options, the contaminants are delayed in reaching the surface water because of the groundwater travel time.

Tables 5 and 6 present the results for all the options. The impacts are only presented for year 250 (time of maximum dose).

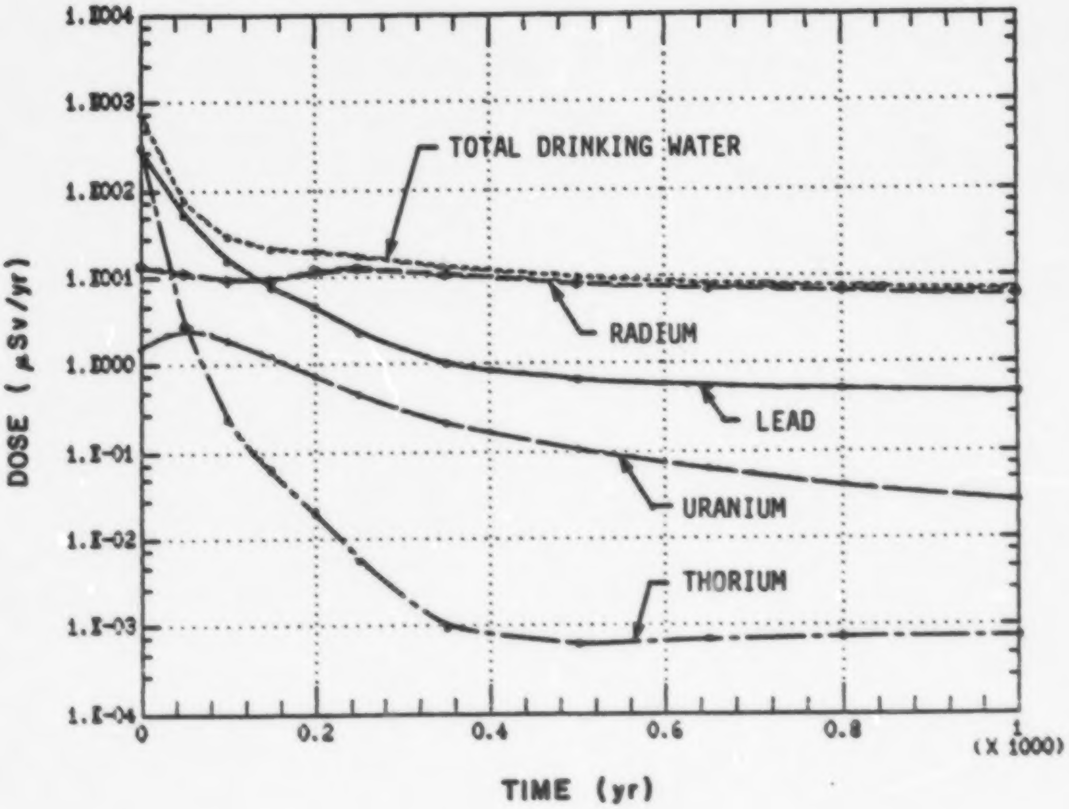
4.3 Cost Impact Criteria

The cost impact criteria are generally readily quantifiable. Cost studies are usually part of the conceptual studies preceding decommissioning of uranium mill tailings.

In the calculation of the costs of the various options, the following considerations were taken into account:

DRINKING WATER DOSE vs. TIME BY RADIONUCLIDE (SCENARIO I)

(from Ref. 1)



NOTE:

GEOMETRIC MEAN VALUES OF 200 TRIALS

FIGURE 8

TABLE 4 BASE CASE (OPTION 1) HEALTH IMPACTS

PARAMETER		RADIOLOGICAL		ARSENIC		NICKEL	
		dose (uSv/a)	risk*	dose (g/a)	risk**	dose (g/a)	risk***
Geometric mean individual dose/risk to critical group							
Chronic exposure	(0 a)	840.					
	(250 a)	80.	9.2E-5	1.8E-3	1.E-3	0.6E-3	1.6E-7
	(1000 a)	23.					
Geometric st. dev.		1.6-1.9					
Extreme event		850.	4.9E-8	19.E-3	5.2E-7	6.4E-3	8.6E-11
Mean individual dose for collective dose calculation							
Chronic exposure							
(local)	(0 a)	400.					
(regional)	(0 a)	80.					
(local)	(250 a)	50.		0.9E-3		0.3E-3	
(regional)	(250 a)	13.		2.3E-4		7.5E-5	
(local)	(1000 a)	18.					
(regional)	(1000 a)	5.					
Extreme event							
(local)		500.		1.0E-2		3.2E-3	
(regional)		125.		2.5E-3		0.8E-3	
Mean collective dose/risk		(man-Sv/a)					
Chronic exposure							
(local)	(0 a)	2.					
(regional)	(0 a)	4.					
(local)	(250 a)	0.25	0.29	4.5	2.5	1.5	4.1E-4
(regional)	(250 a)	0.84	0.97	16.	8.8	4.9	1.3E-3
(local)	(1000 a)	0.09					
(regional)	(1000 a)	0.32					
Extreme event							
(local)		2.5	1.4E-4	50.	1.4E-3	16.	2.2E-7
(regional)		8.1	4.7E-4	163.	4.5E-3	52.	7.0E-7

* Radiological risk factor 1.65E-2/man-Sv[4] becomes 1.16 cancer fatalities in a population receiving 1 man-Sv/a over a 70 year exposure.

** Arsenic risk factor 0.55/g/a lifetime cancer fatalities[54]

*** Nickel risk factor 2.7 E-4/g/a lifetime cancer fatalities[55]

TABLE 5 RADIOLOGICAL IMPACTS
(at 250 years)

	Units if required	Base Case	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
RADIOLOGICAL - PUBLIC Collective Risk mean - local	number of fatal cancers in 70 years	2.9E-01	5.9E-01	1.4E-01	5.8E-02	2.0E-03	< 1.0E-4	1.2E-02
time	years	250	250	250	250	250	250	250
mean - regional	number of fatal cancers in 70 years	9.7E-01	1.9E+00	4.9E-01	1.9E-01	9.7E-03	< 1.0E-4	4.0E-02
time	years	250	250	250	250	250	250	250
extreme event - local	fatal cancers	1.4E-04	1.4E-04	1.4E-04	7.0E-05	1.4E-05	1.4E-05	1.4E-04
extreme event - regional	fatal cancers	4.7E-04	4.7E-04	4.7E-04	2.4E-04	4.7E-05	4.7E-05	4.7E-04
Individual Risk geometric mean	individual risk of fatal cancer in 70 yrs	9.2E-05	1.8E-04	4.6E-05	1.8E-05	9.2E-07	< 1.0E-8	4.6E-06
time	years	250	250	250	250	250	250	250
extreme event	fatal cancer risk	4.9E-08	4.9E-08	4.9E-08	2.5E-08	4.9E-09	4.9E-09	4.9E-08
RADIOLOGICAL - OCCUPATIONAL risk	number of cancer fatalities	-	-	3.3E-04	5.0E-04	5.0E-04	3.3E-03	-
collective dose	man-Sv	-	-	2.0E-02	3.0E-02	3.0E-02	2.0E-01	-

TABLE 6 NON-RADIOLOGICAL HEALTH IMPACTS
(at 250 years)

	Units if required	Base Case	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
NON-RADIOLOGICAL - PUBLIC Collective Risk mean - local	number of fatal cancers in 70 years	2.5	2.5	1.3	0.5	0.3	0.1	2.5
time	years	250	250	250	250	250	250	250
mean - regional	number of fatal cancers in 70 years	8.8	8.8	4.4	1.8	0.9	0.4	8.8
time	years	250	250	250	250	250	250	250
extreme event - local	fatal cancers	0.0014	0.0014	0.0007	0.0003	0.0001	< 0.0001	0.0014
extreme event - regional	fatal cancers	0.0045	0.0045	0.0023	0.0009	0.0005	0.0002	0.0045
Individual Risk geometric mean	individual risk of fatal cancer in lifetime (70 years)	1.0E-03	1.0E-03	5.0E-04	2.0E-04	1.0E-04	5.0E-05	1.0E-03
time	years	250	250	250	250	250	250	250
extreme event	fatal cancer risk	5.5E-08	5.5E-08	2.8E-08	1.1E-08	5.5E-09	2.8E-09	5.5E-08

Operating and capital costs were expressed in terms of a present value (in 1982 dollars) by assuming a 10% interest rate and a 5% inflation rate which remains constant over the period calculated. For simplicity, in the actual calculations, a net interest rate of 5% was used.

For the purposes of this study, all the costs were distributed over one site. This assumption is especially important for options 2 in the distribution of the mill circuit cost and options 4 and 5 in which cover material may not be available locally for more than one site.

Option 1: the do nothing option involved no cost and was included to provide a baseline option from which to evaluate the various impacts of the other options.

Option 2: a pyrite floatation circuit is added to the existing mill to reduce pyrite content and add limestone to the final one meter of tailings. Costs are based on a 1984 NUTP report[56].

Option 3: costs are based on the 1984 MacLaren report[53].

Option 4: tailings preparation work as in option 3, preparation of borrow area, upgrading of road from borrow area to tailings, excavation and placement of soil cover.

Costs are based on the MacLaren report[53].

Option 5: same as option 4 with the addition of 14 m deep holes drilled 1 m into bedrock from the top of the dam at 1 m intervals in two rows 1 m apart and the slurrying of bentonite into the bottom 5 m of these holes to produce a grout curtain and prevent seepage from the dam. Cost of grouting is based on a 1982 EPA report[57].

Option 6: the costs of this option are based on the MacLaren report[53].

Option 7: it is assumed that one technician is assigned full time to operate the treatment facility and inspect the site.

The cost break-down of the various options is given in Table 7.

In order to estimate the cost of failure, the results of the extreme event scenario are used. Generally, the health impact following dam failure and flooding was not high enough to warrant clean-up other than remedial works on the disposal facility itself. This would involve repairs to the dam and to the cover. These were estimated from the MacLaren's report[53] and are included together with the total cost of each option in Table 8.

4.4 Other Impact Criteria

There are no quantitative measures for most of the impacts considered in this section. The possible exceptions are the environmental impacts in which water and air quality measures can be found as well as death rates of wildlife species; however, there are certain parameters such as the effects on wildlife population patterns that are generally difficult to quantify objectively. In general, the criteria in this branch are qualitative and contain considerable subjective input.

These impacts, being largely qualitative in nature, were quantified in the present example, using a scale of 1 to 10 to measure the performance of each option. Two scales were used. An objective scale was used in order to provide an objective measure for the perfomance under each criterion. A relative scale was also included in which 10 denotes the option with the best performance and 1 the option with the worst performance and the rest relatively spaced between 1 and 10. The scale was included merely to illustrate the relative performance of the options and is not used in any of the evaluation technique applications.

The measures of the performance of the options under the various other impact criteria are given in Figures 9 - 28. Both the relative and the objective scales are indicated on these figures as well as any option specific comments. These figures describe a simple ranking system that is subjective; however, it or some variation may be used in a multi-criteria analysis. This will be discussed in greater detail in the next chapter.

The performance of the considered decommissioning options under the evaluation criteria using the relative scale described in this section are summarized on Table 9.

TABLE 7 COST IMPACT FOR TAILINGS DECOMMISSIONING

Option	Component	Cost (1982$)
1	base case	$ 0.
2	mill circuit capital cost	$ 9,230,000.
	limestone addition	$ 60,000.
	operating cost (one year operation)	$ 3,233,000.
	total	$12,523,000.
3	limestone addition	$ 600,000.
	tailings preparation & vegetation	$ 1,350,000.
	total	$ 1,950,000.
4	soil cover	$ 9,800,000.
	tailings preparation and vegetation	$ 2,000,000.
	total	$11,800,000.
5	soil cover	$ 9,800,000.
	tailings preparation and vegetation	$ 2,000,000.
	dam grouting - drill holes (14 m)	$ 1,200,000.
	- grout (5m)	$ 1,500,000.
	total	$14,500,000.
6	excavate tailings and haul	$66,000,000.
	prepare site	$ 2,900,000.
	place tailings	$ 3,800,000.
	cover tailings	$12,500,000.
	total	$84,200,000.
7	renew dam and treatment plan	$ 1,500,000.
	operation costs	$ 1,800,000.
	total	$ 3,300,000.

TABLE 8 COST IMPACTS

	Units if required	Base Case	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
Capital Cost	M$ (1982$)	0	9.2	2	11.8	14.5	84.2	0
Operating Cost	M$ (1982$)	0	3.2	0	0	0	0	3.3
Cost of Failure	M$ (1982$)	0.2	0.2	2.2	6	1.5	1.5	0.2

TABLE 9 OTHER IMPACT CRITERIA

	Units if required	Base Case	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
ENVIRONMENTAL Water Quality	objective scale	2	2.5	4.5	5.5	6.9	8	6.2
Air Quality	objective scale	5	5	7.5	10	10	10	5
Effect on Wildlife terrestrial	objective scale	5.2	5.2	5	6	6	6	5.2
aquatic	objective scale	4	4.3	4.8	5.3	5.8	6	5.5
SOCIAL/POLITICAL local impacts (employment)	objective scale	4	4.5	4.5	5.2	5.6	7	7
national interest	objective scale	3	3	8	7	6.4	3.6	3
provincial interest	objective scale	3	3	8	7	6.5	4.2	3
international acceptability	objective scale	4	4	5.7	7.2	8	5.7	4
public acceptability	objective scale	3	3.5	5.2	5.8	6.2	7	3.5
institional control	objective scale	3.5	3.5	3.5	4.5	4.5	5	2
aesthetics	objective scale	5	5	7.8	8.8	8.8	10	5
land usage	objective scale	1	1	1	3.2	3.2	5	1
local impacts (other)	objective scale	4	4	4.6	5	5	6	2
material requirements impact	objective scale	10	7.8	8.8	5.5	5	6.2	10
TECHNICAL reliability	objective scale	1	1.5	1.5	2.6	4.3	5.5	6
reliance on natural barriers	objective scale	3	3	3.5	4.5	4.5	6	3
flexibility to cope with future change	objective scale	8.5	8.5	8.5	5.5	4.5	3	10
previous experience with decomm. option	objective scale	6	2	5.2	3.5	2.3	2.3	3
complexities of the decomm. option	objective scale	10	2	9	6	4	3	1
volume reduction	objective scale	1	1	1	1	1	1	1

Figure 9 : Performance of Options Under

Criterion Air Quality

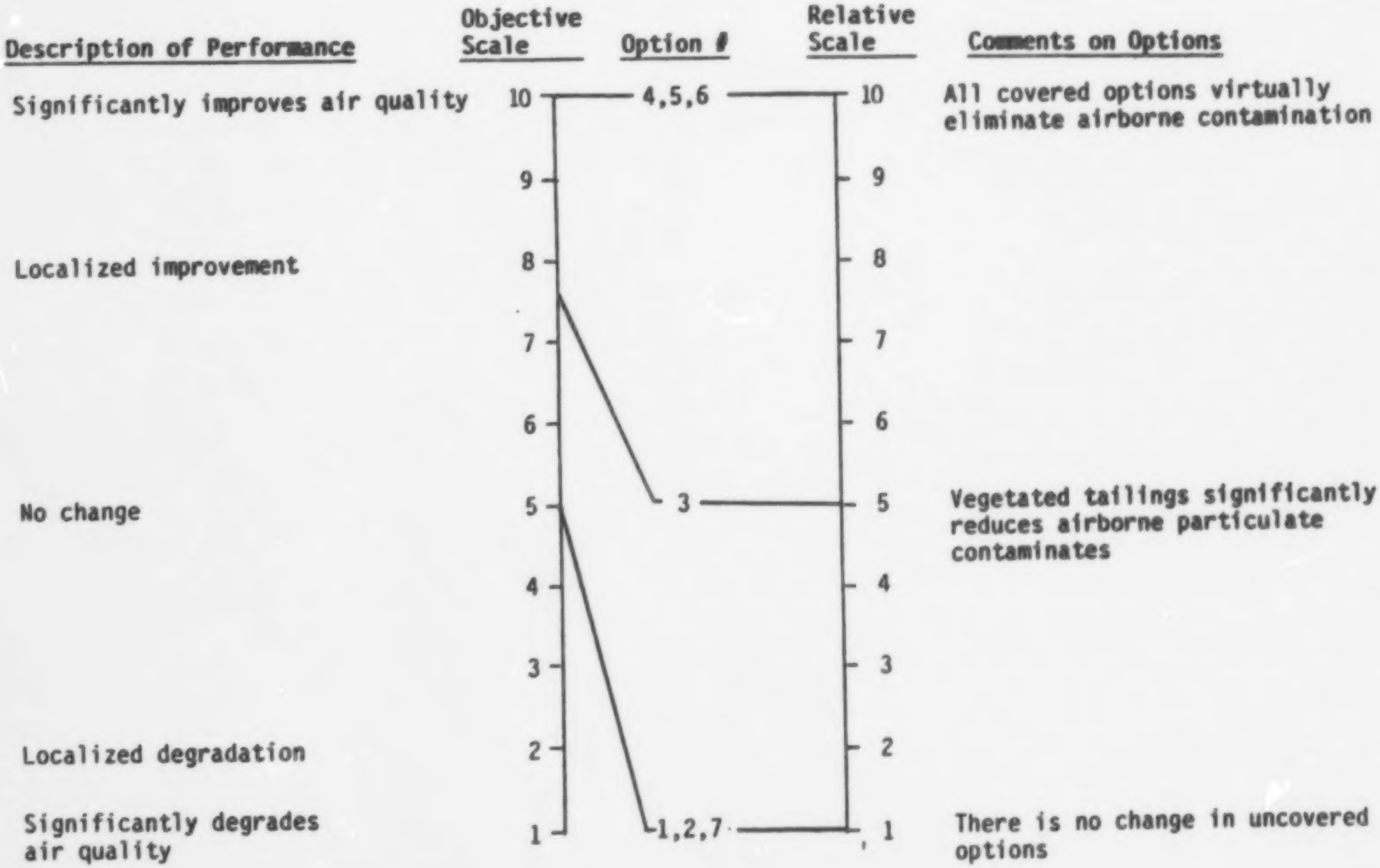


Figure 10 : Performance of Options Under

Criterion Public Acceptability

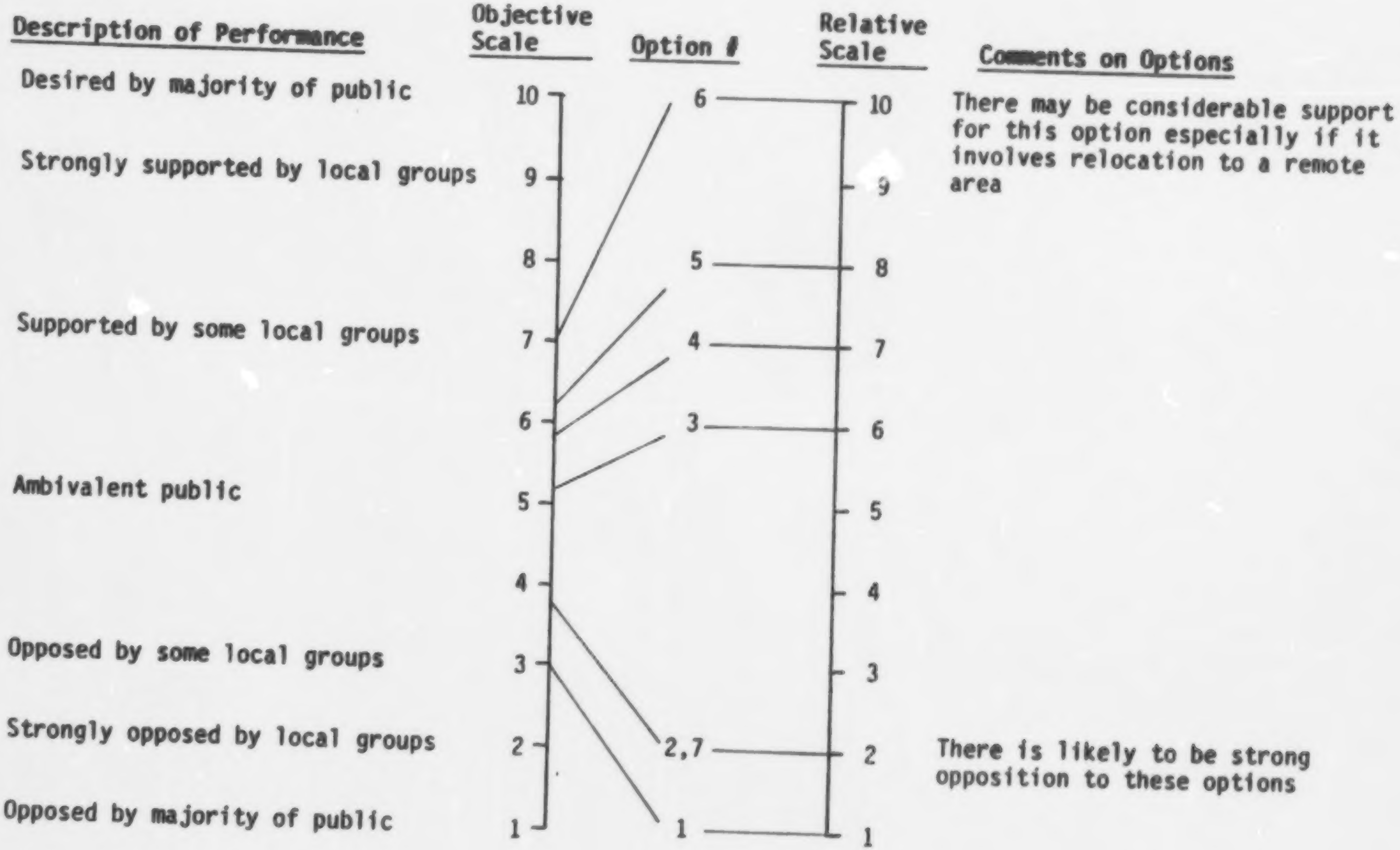
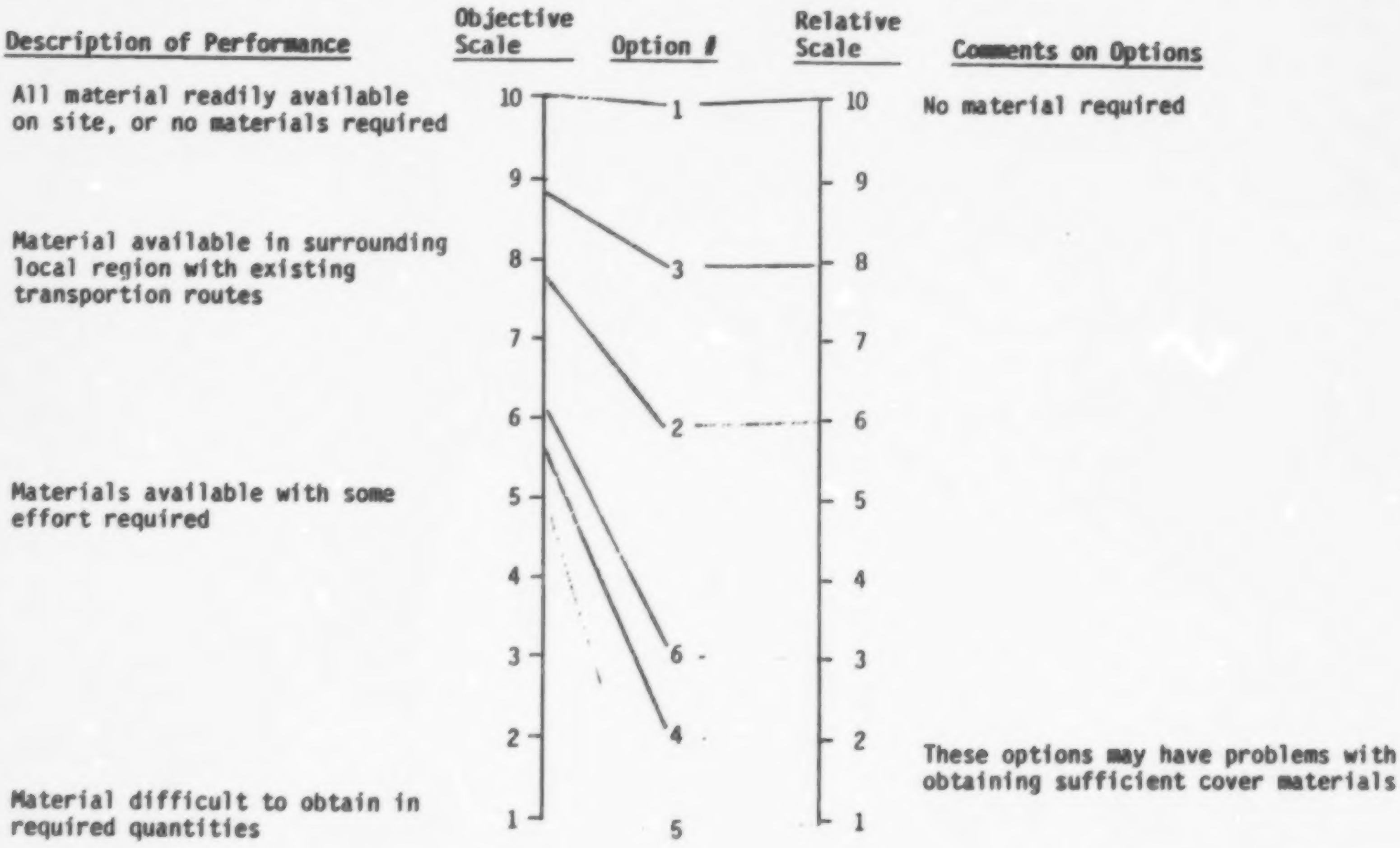

Description of Performance
Objective Scale
Option #
Relative Scale
Comments on Options
Desired by majority of public
Strongly supported by local groups
Supported by some local groups
Ambivalent public
Opposed by some local groups
Strongly opposed by local groups
Opposed by majority of public
10
9
8
7
6
5
4
3
2
1
6
5
4
3
2,7
1
10
9
8
7
6
5
4
3
2
1
There may be considerable support for this option especially if it involves relocation to a remote area
There is likely to be strong opposition to these options

Figure 11 : Performance of Options Under

Criterion Material Requirements Impacts



Description of Performance

All material readily available on site, or no materials required

Material available in surrounding local region with existing transportion routes

Materials available with some effort required

Material difficult to obtain in required quantities

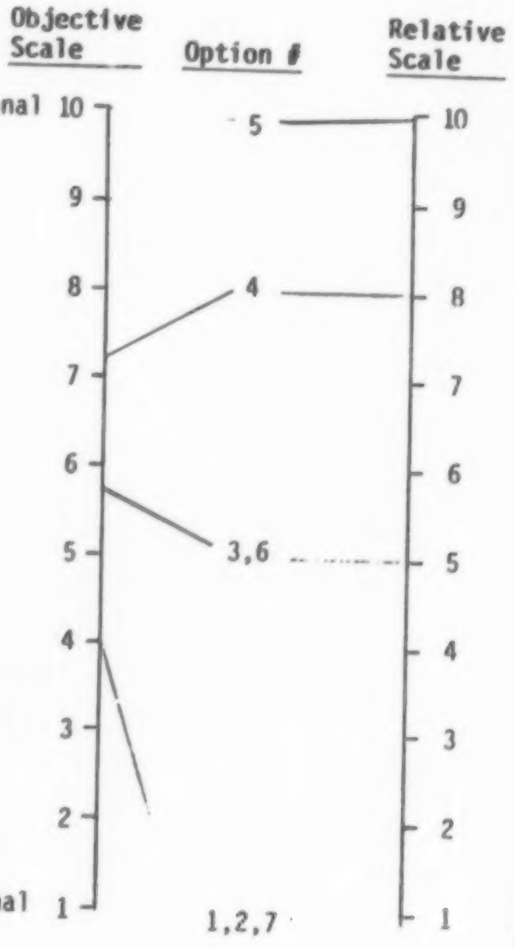
Comments on Options

No material required

These options may have problems with obtaining sufficient cover materials

Figure 12 : Performance of Options Under

Criterion International Acceptability



Description of Performance

Desired by majority of international technical community

Ambivalent

Opposed by majority of international technical community

Comments on Options

Options 4 and 5 are those generally favoured in areas where cover soil is available

These options are likely to be opposed by some members

Figure 13 : Performance of Options Under

Criterion Land Usage

Description of Performance

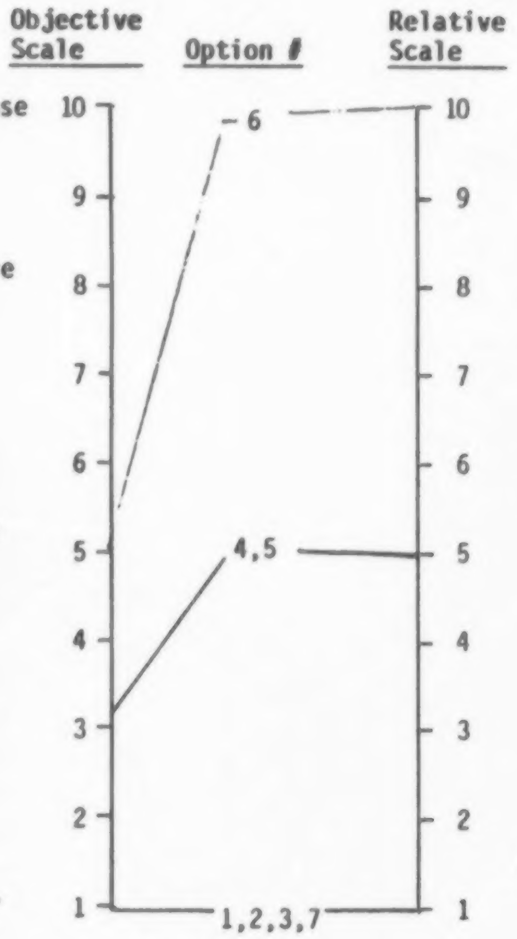
Permits use of land for any purpose (agricultural)

Land useful for certain productive purposes (e.g. building)

Land useful for most recreational purposes

Land useful for only restricted recreational purposes

No possible use of land for other purposes



Comments on Options

Relocation could be to area specifically suitable for recreation

Covered options may allow some recreational activities over tailings

Uncovered option preclude use of tailings area for other purposes

Figure 14 : Performance of Options Under

Criterion National Interest

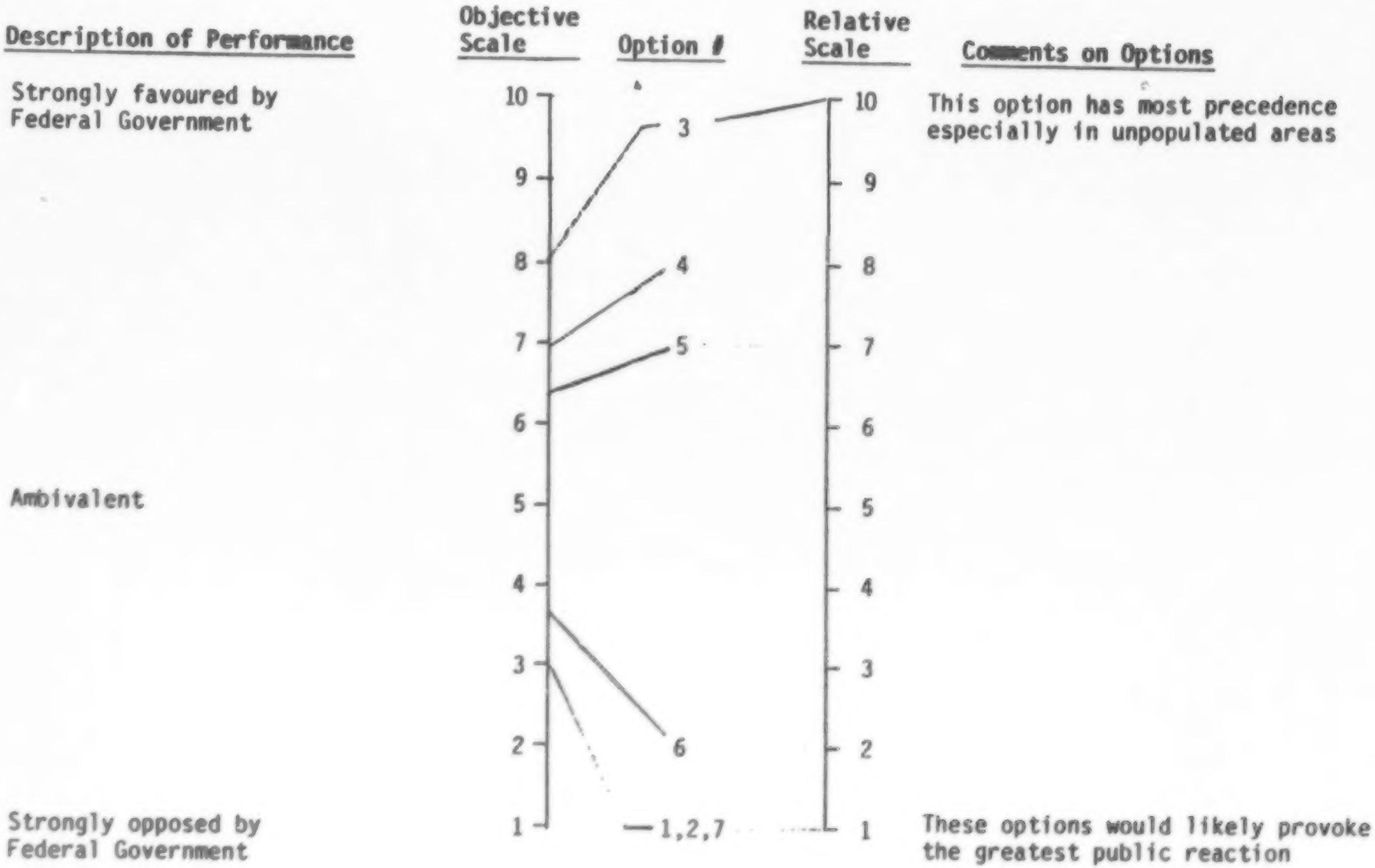


Figure 15 : Performance of Options Under

Criterion Aesthetics

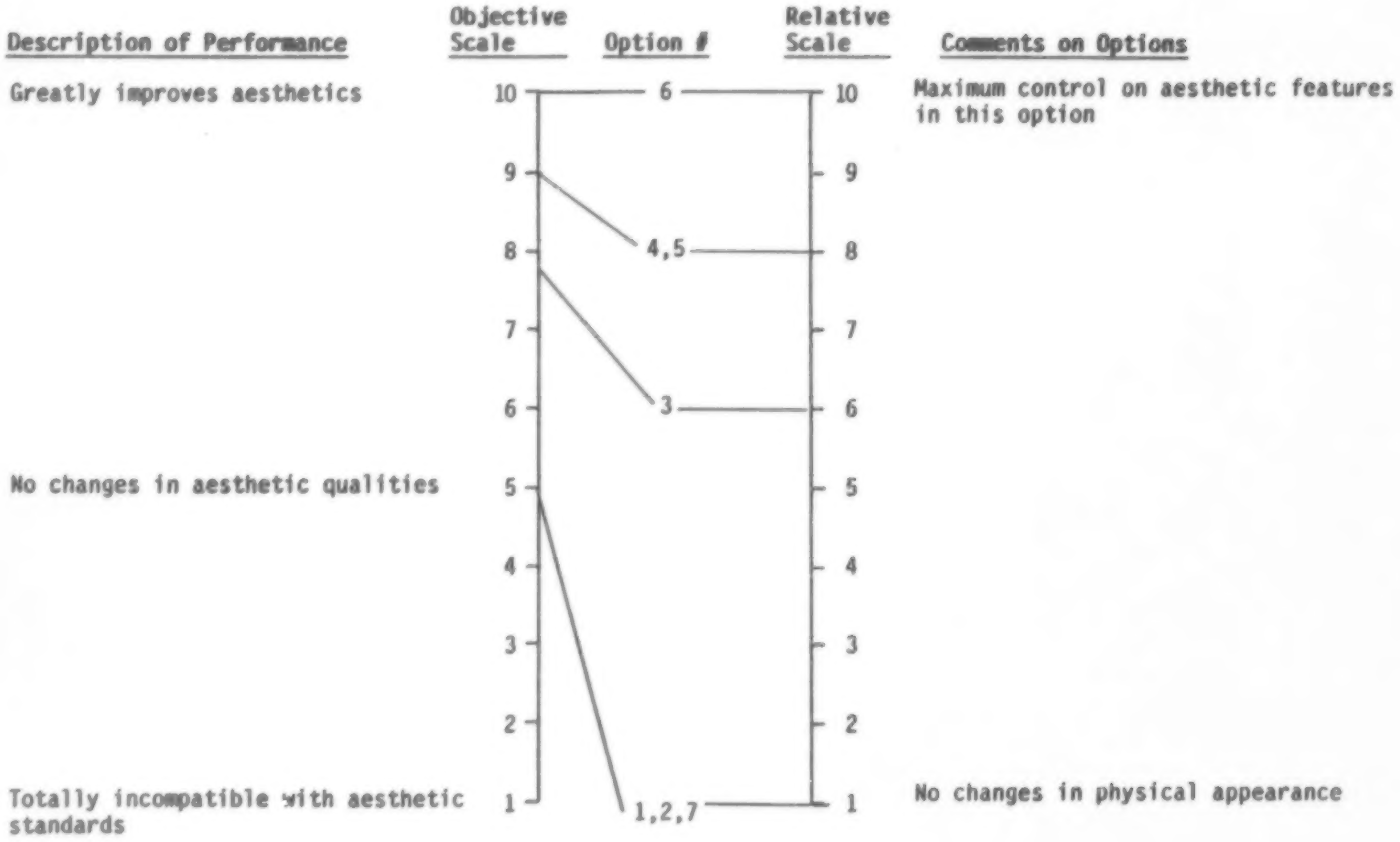

Description of Performance
Objective Scale
Option #
Relative Scale
Comments on Options
Greatly improves aesthetics
10
6
10
Maximum control on aesthetic features in this option
9
9
4,5
8
8
7
7
3
6
6
No changes in aesthetic qualities
5
5
4
4
3
3
2
2
Totally incompatible with aesthetic standards
1
1,2,7
1
No changes in physical appearance

Figure 16 : Performance of Options Under

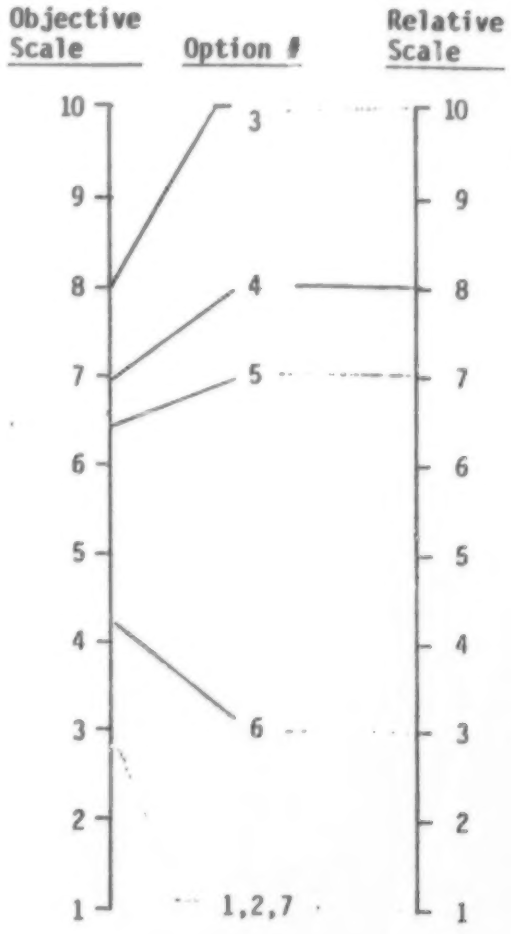
Criterion Provincial Interest

Description of Performance

Strongly favoured by Provincial Government

Ambivalent

Strongly opposed by Provincial Government


Objective Scale
Option #
Relative Scale
10
9
8
7
6
5
4
3
2
1
3
4
5
6
1,2,7
10
9
8
7
6
5
4
3
2
1

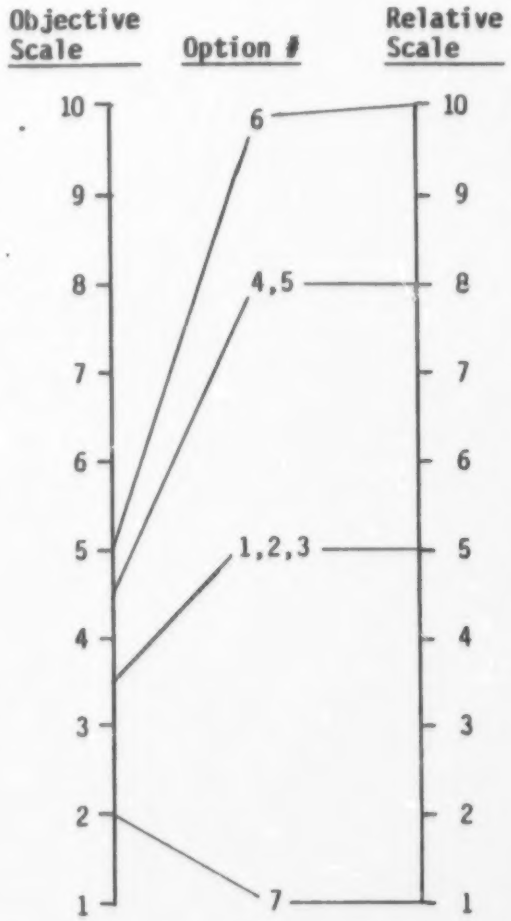
Comments on Options

This option has the most precedence especially in unpopulated areas

These options would likely provoke the greatest public reaction

Figure 17 : Performance of Options Under

Criterion Institution Control Requirements



Description of Performance	Objective Scale	Comments on Options
No institutional control	10	Closest to a walk-away situation for a surface disposal option. Only administrative control required
Short term passive	8	
Short term active control	6	
Long term passive control	5	These options would likely require maintenance of a fence and monitoring of surface waters
Long term active institutional control	1	Long term maintenance and operation

Figure 18 : Performance of Options Under

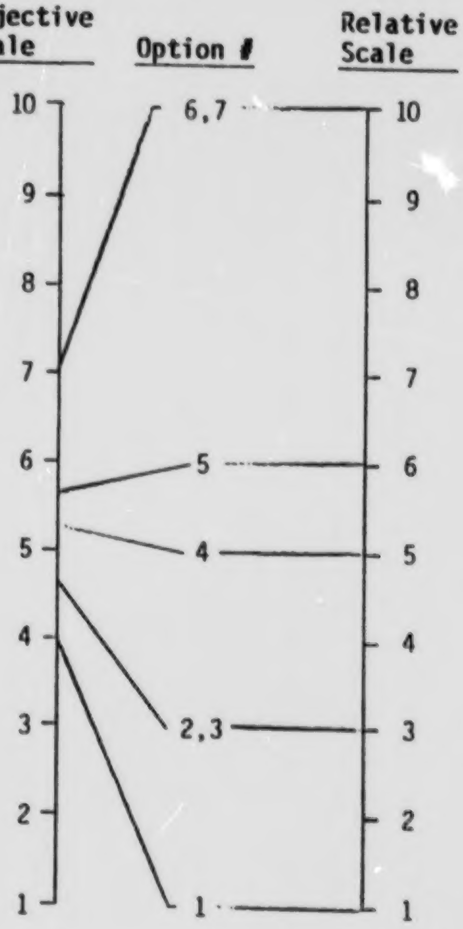
Criterion Local Impacts (employment)

Description of Performance

Source of high long-term employment to local community

No effect on employment in the community

Results in high unemployment in community


Objective Scale
Option #
Relative Scale
10
9
8
7
6
5
4
3
2
1
6,7
5
4
2,3
1
10
9
8
7
6
5
4
3
2
1

Comments on Options

These options would provide some employment during implementation

This option may result in adverse effects on some industries and decrease employment

Figure 19 : Performance of Options Under

Criterion Local Impacts (other)

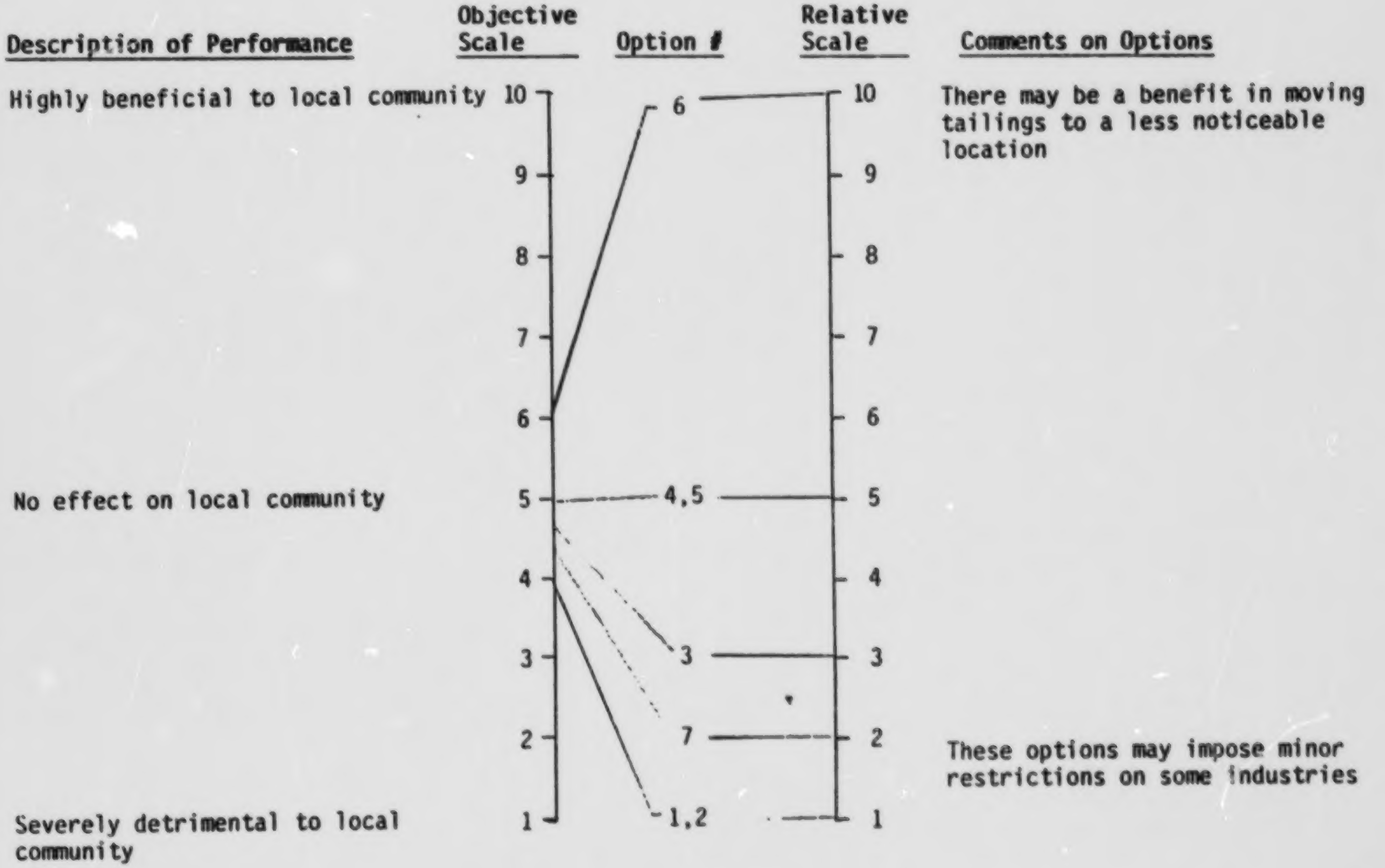


Figure 20 : Performance of Options Under

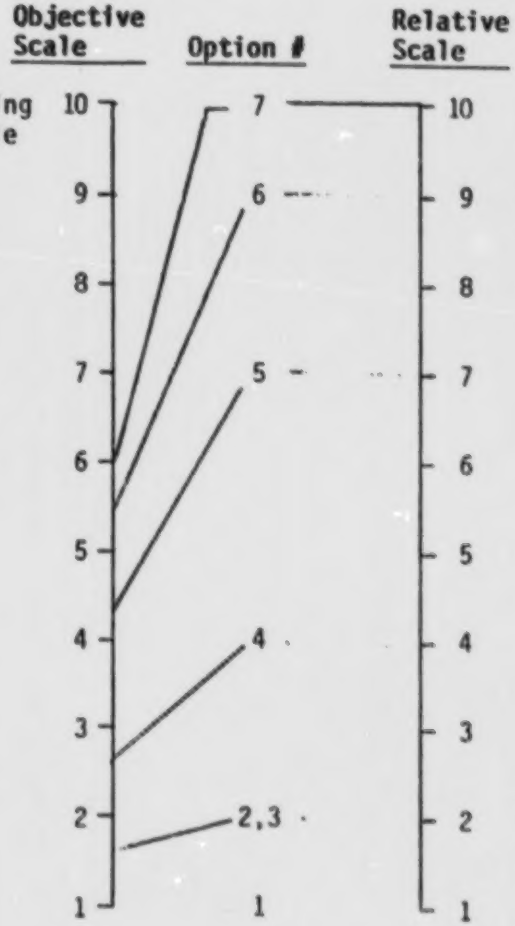
Criterion Reliability

Description of Performance

Complete reliability in maintaining performance throughout predictable lifetime

Average reliability

Poor system reliability



Comments on Options

Major source of unreliability would be manpower related

Most likely of engineered options to perform reliably.

No containment engineered, thus poor performance is expected with options 1 to 3

Figure 21 : Performance of Options Under

Criterion Natural Barriers

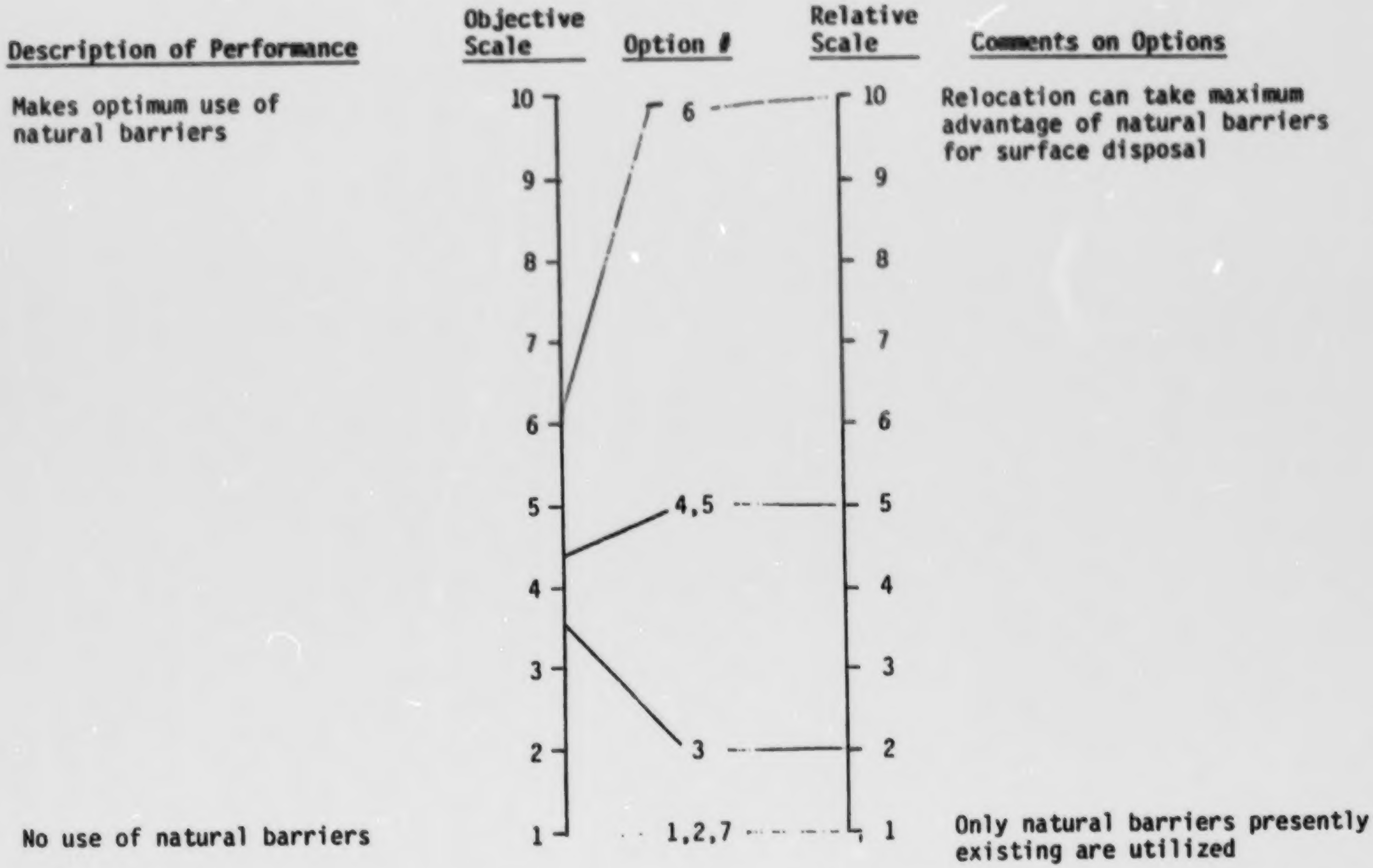


Figure 22 : Performance of Options Under

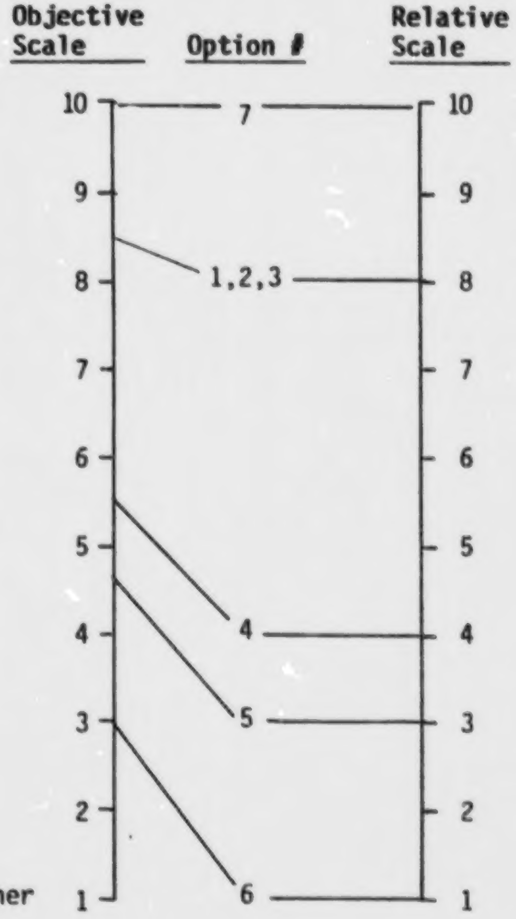
Criterion Flexibility

Description of Performance

Easy to change to another option in future, if desired

Possible to change to another option, but effort is required

Very difficult to change to another option in future, if desired



Comments on Options

No change from situation at pre-decommissioning

Some remedial work may be necessary to bring option to pre-decommissioning state (e.g. dam repairs)

Depending on amount of engineering involved in the option, it becomes increasingly difficult to change to another option.

Figure 23 : Performance of Options Under

Criterion Experience

Description of Performance	Objective Scale	Relative Scale	Comments on Options
Large amount of experience over very long period of time	10	10	No experience necessary
	9	9	
Large amount of experience over short period, some long term experience	8	8	Main type of decommissioning used on all types of tailings
	7	7	
Significant short term experience, very little long term	6	6	
	5	5	
Some short-term experience, no long term	4	4	
	3	3	Very little experience with most of the options
Very little experience of any kind	2	2	
No experience	1	1	

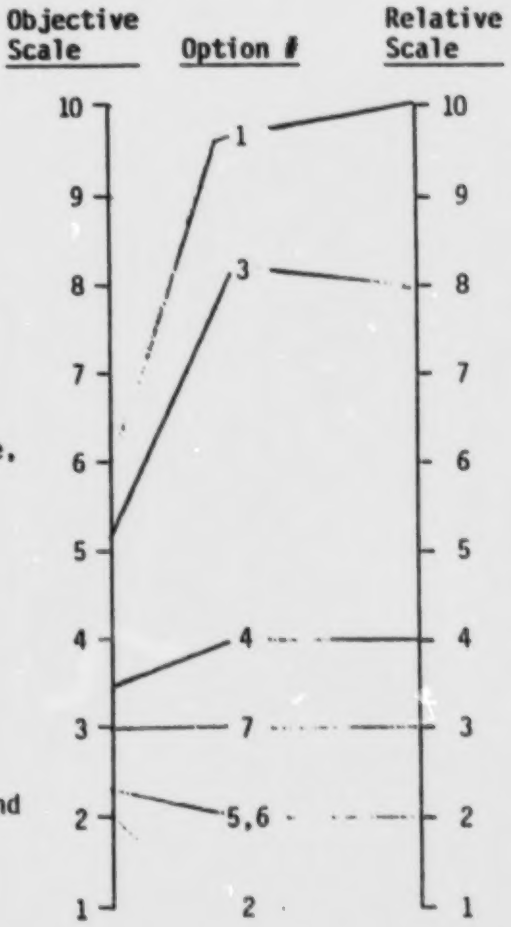
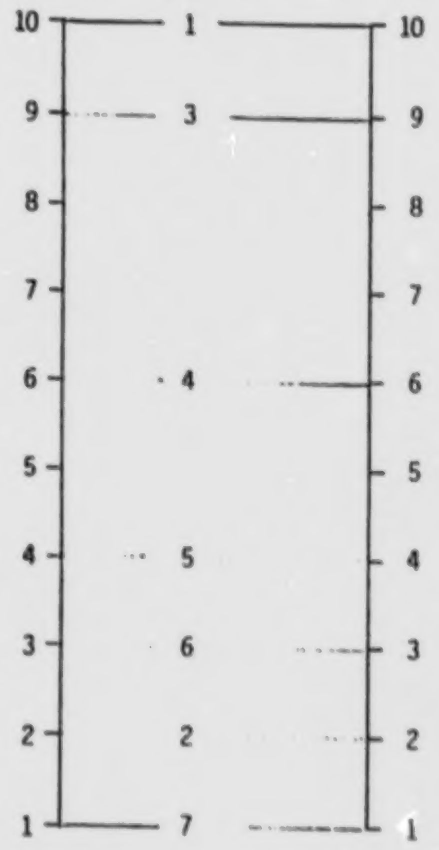


Figure 24 : Performance of Options Under

Criterion Complexity



Description of Performance	Objective Scale	Option #	Relative Scale	Comments on Options
Straightforward, simple, easy to implement	10	1	10	No action
	9	3	9	Minimal work on tailings
	8		8	
	7		7	
	6	4	6	Routine cover placement operation
Average complexity	5		5	
	4	5	4	Extensive drilling, in addition to 4
	3	6	3	Large scale moving operation, in addition to 5
	2	2	2	Well tested changes in existing mill operation
Highly complex, requires high level of skill to implement	1	7	1	Perpetual maintenance

Figure 25 : Performance of Options Under

Criterion Volume Reduction

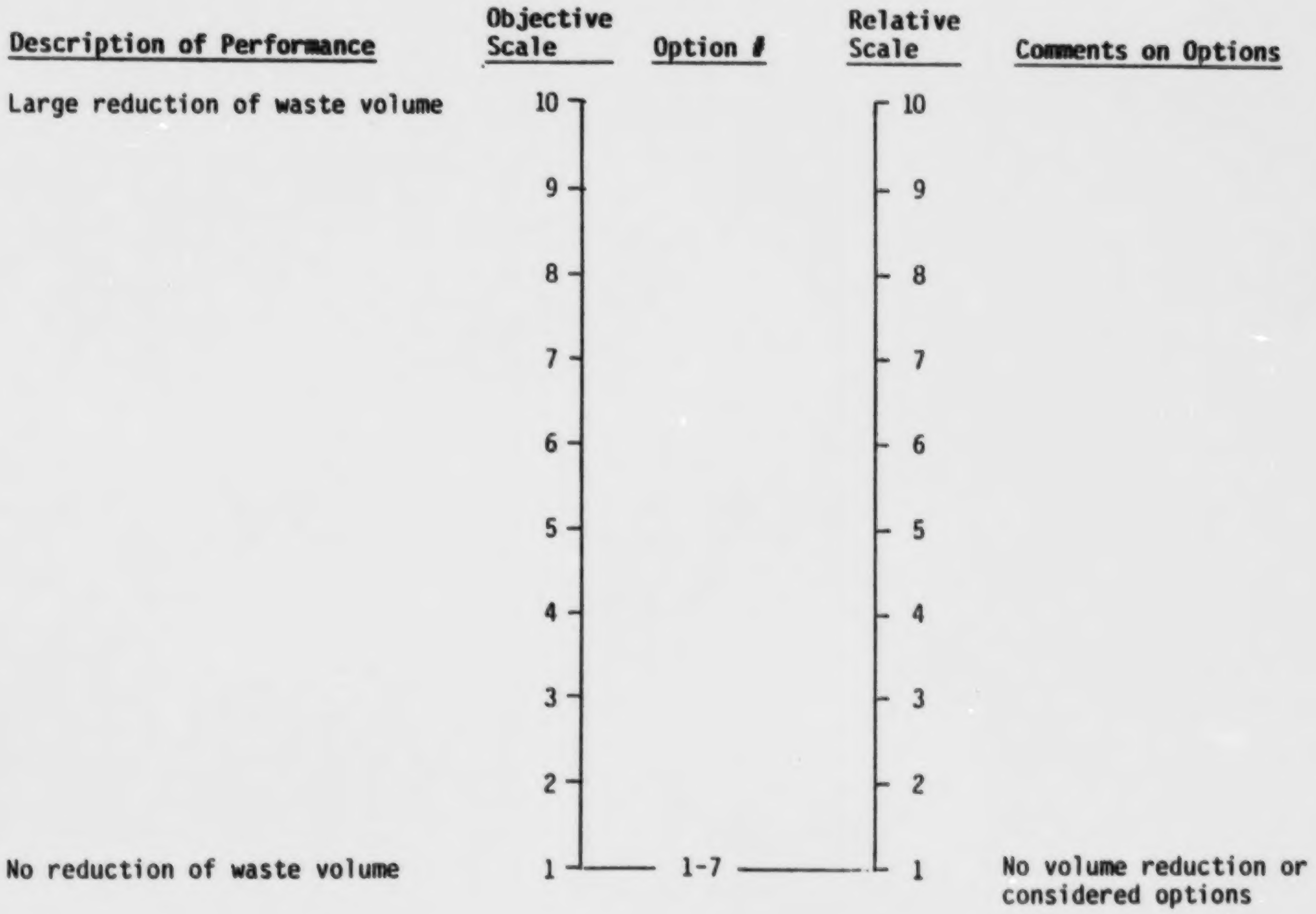


Figure 26 : Performance of Options Under

Criterion Wildlife (terrestrial)

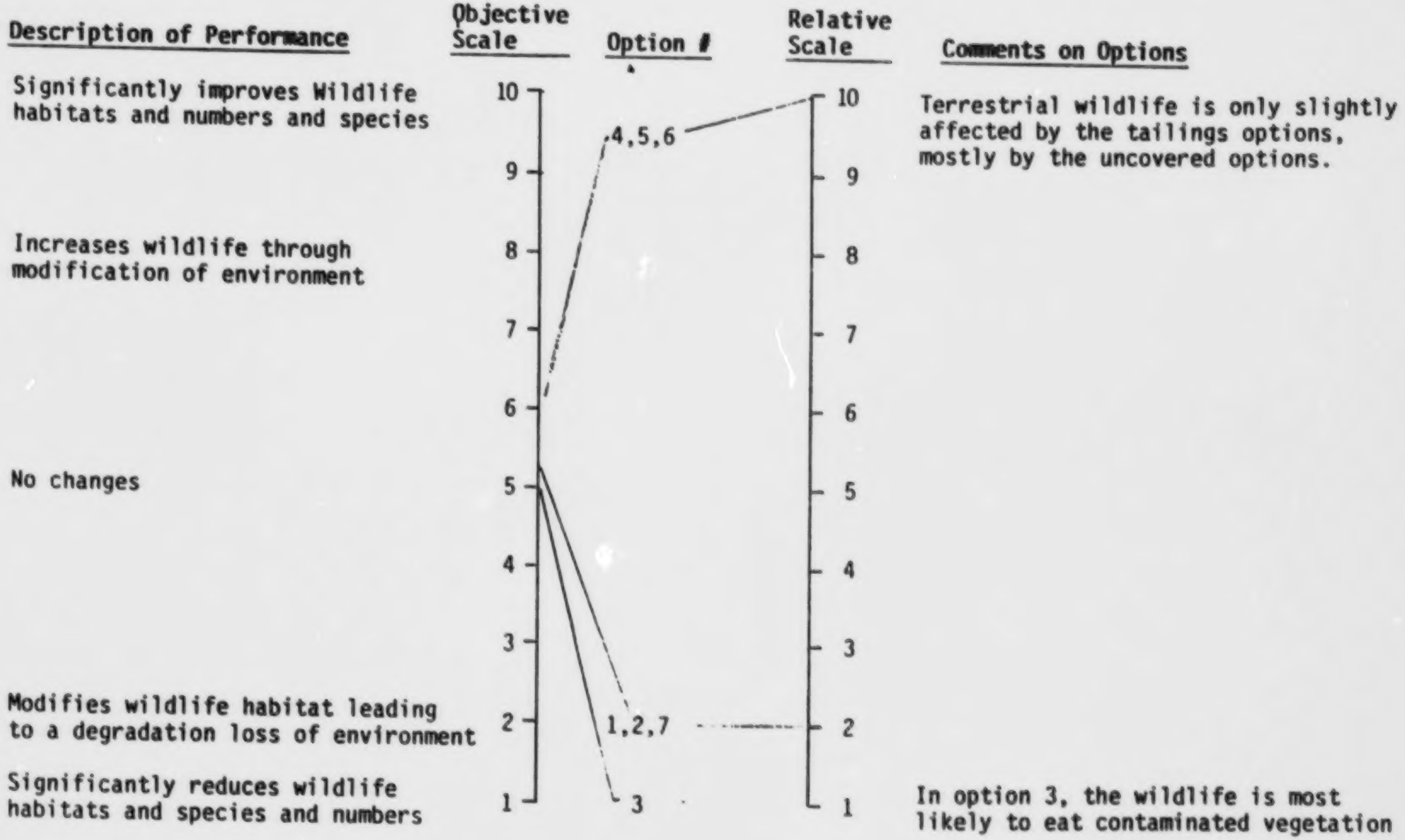


Figure 27 : Performance of Options Under

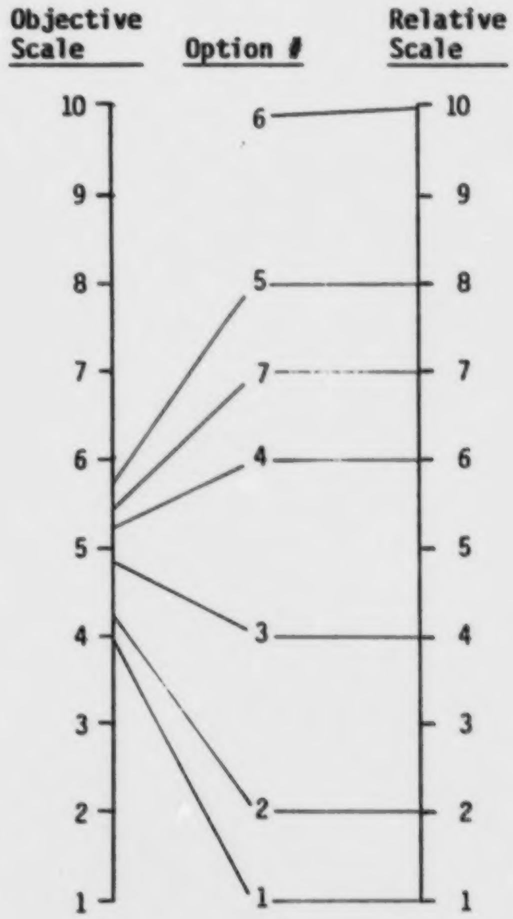
Criterion Wildlife (Aquatic)

Description of Performance

Significantly improves habitat and numbers and species

No changes

Significantly reduces wildlife, habitat and species and numbers



Objective Scale
Option #
Relative Scale
10
9
8
7
6
5
4
3
2
1
6
5
7
4
3
2
1
10
9
8
7
6
5
4
3
2
1

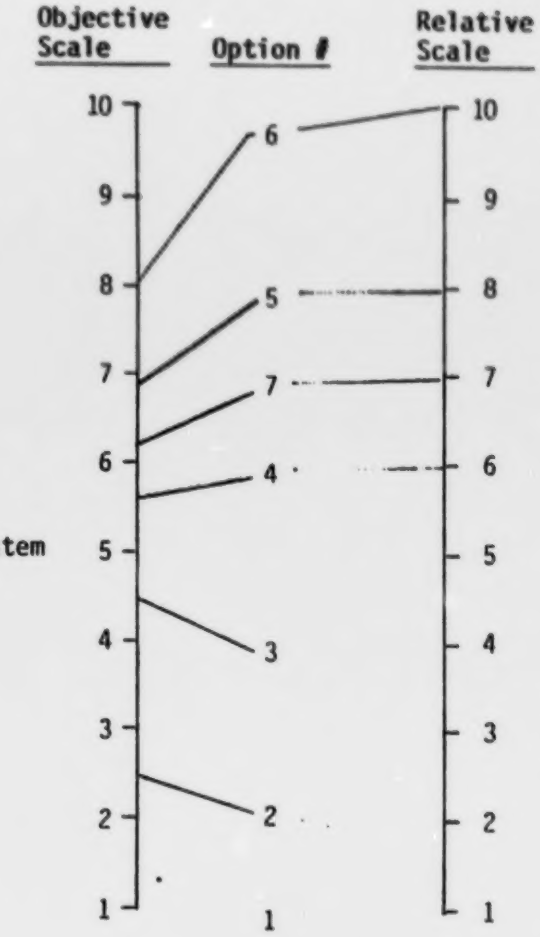
Comments on Options

This option may result in net benefit since loading on surface water system is significantly decreased

There is a deterioration in water quality when treatment is discontinued

Figure 28 : Performance of Options Under

Criterion Water Quality



Description of Performance

Significantly increases water quality

Localized improvement

No changes reflected within system

Localized degradation

Significantly reduces water quality

Comments on Options

Minimum discharge to surface water

Improvement in pH in short term

Upon abandonment, there is no further treatment of seepage

5.0 APPLICATION OF DECISION METHODS

5.1 Overview

In the previous sections a detailed discussion of decision methods, their applications and a description of the tailings decommissioning problem were presented. In Section 3.4, the decision methods were evaluated and cost/benefit, cost-effectiveness, and multi-attribute utility theory selected as suitable for use in the decommissioning problem. In this chapter, a number of the decision techniques (cost-benefit, cost-effectiveness, MAUT and a decision system) will be applied to the previously developed decommissioning options. The style of these sections will differ somewhat from the previous discussion sections, in that, wherever possible, a step-by-step tutorial or guide to the use of these methods will be presented. Each section will have a brief overview of the procedure followed by a detailed calculation and application section. Where a side discussion on peripheral aspects of the problem or procedure are useful, these will be presented in the form;

(Note: An aside concerning a relevant, but not, directly required aspect of the technique.)

The data required for the various analysis, ie. the description of the options, has already been presented in Chapter 4. The data used in the current section is based on the Section 4 data and modified and/or scaled as required for a particular decision method.

5.2 Cost Benefit - As a Procedure

5.2.1 Overview

Two approaches are possible in the application of a cost-benefit procedure. The first can be considered to be the direct application of costs and the converted dollar value of the dose reductions compared to the base case (Option 1). The second approach, which is much more extensive and complex, involves the conversion of other criteria to a dollar value, but which do not have a readily measured dollar value (e.g. aesthethics). Some of the other criteria, such as impact on local economy could be measured in a dollar value, by extensive economic modelling of each of the options. In effect, this approach of assigning dollar values to other criteria, is equivalent to weighting methods used in MAUT.

Note: The cost-benefit analysis technique recommended by the ICRP attempts to do this for collective and individual dose criteria using a linear programming relationship,

$$\gamma = \alpha S + \beta \sum_{j} Nj \times fj\ (Hj)$$

where,

S	is the collective dose equivalent,
α	is the monetary value assigned to unit collective dose,
β	is the monetary value assigned to relate the aggregate value of the more subjective criteria to individual dose;
fj(Hj)	is the average dose contribution from an individual of an exposed group j (modified average individual dose);
Hj	is the average dose equivalent in the individuals of group j;
Nj	is the number of individuals in group j.

However, this technique is less transparent in incorporating multiple criteria than the MAUT and will not be discussed further in the report. Details of this method are contained in ICRP83, International Commission on Radiological Protection (ICRP), 1983, "Cost-Benefit Analysis in the Optimization of Radiation Protection, ICRP Publication 37, Annals of the ICRP, Vol. 1C, No.2/3.

As the purpose of this section is to show the procedure for a cost-benefit analysis, only the costs and dose factors will be considered. In this discussion, the term "benefit" is used to define the health impacts or reduction in health impacts compared to the base case. Though this is not strictly the complete "benefit" of an option, it is consistent with previous cost/benefit analysis in the nuclear industry.

Main Steps in the Procedure

1. Compile the total cost for each option discounted to present value. Compile the cumulative total health impacts (either dose, cancers or some other effect).

2. Convert the health impact estimates to dollar values.
3. Calculate the cost/benefit ratio of each option.
4. Compare options.

5.2.2 Details of Main Steps

Step 1. Compile cost data and health impact data.

The cost of each option has been described and calculated in Section 4.4. Operating costs were discounted to present value dollars for comparison to the capital costs.

Note 1.1 If one were to form, hypothetically, an option or combination of options that would be used some time in the future (for example delay the construction of the treatment plant for 50 years), discounting these projected costs to current dollars would provide a method for comparing options.

Note 1.2 As well, uncertainty, either in current estimates or in projected estimates could be handled as a range of cost data and health impact data, for example, Option 2 has a total cost range of $9.7 to $15.6 million, with an "best-estimate" of $12.4 million. This would then be carried through the calculation to obtain the range of cost/benefit ratios. One could then decide on the best option on the basis of "best-estimate", worst cost scenario or best cost scenario. For simplicity in the current example, only the "best-estimate" values of both cost and health impact are used. It should be noted that the choice of health impact scenario may greatly influence the ranking of options.

A compilation of the total costs and impacts of the various options is given in Tables 10 to 12.

The cumulative dose (cumulative with time) is required in order to compare total costs over time with total benefits over time.

Note 1.3 There are numerous papers discussed in Appendix I on methods of handling future health effects, how far into the future health effects should be considered (see for example VAN83) and over what population group the population dose should be calculated. It is not the purpose of this study to add to the current discussions on this area. Other approaches, including no discounting and discounting at a rate equal to the capital cost discounting, can also be utilized.

For the current study, the cumulative cancers for the local population, at times 100, 250, 500 and 1000 years were estimated. These values without

Table 10 - Costs and Benefits (Arsenic and Nickel)

		Option						
		1	2	3	4	5	6	7
Cost of option		$0	$12,400,000	$2,000,000	$11,800,000	$14,500,000	$84,200,000	$3,300,000
Cancers	year 100	3.6	3.6	1.9	0.7	0.4	0.0	0.4
	year 250	8.9	8.9	4.6	1.8	1.1	0.0	1.1
	year 500	17.9	17.9	9.3	3.6	2.1	0.0	2.1
	year 1000	35.7	35.7	18.6	7.1	4.3	0.2	4.3
Costs of cancers	year 100	$3,200,000	$3,200,000	$1,700,000	$600,000	$400,000	$0	$400,000
	year 250	$8,000,000	$8,000,000	$4,200,000	$1,600,000	$1,000,000	$0	$1,000,000
	year 500	$16,100,000	$16,100,000	$8,400,000	$3,200,000	$1,900,000	$0	$1,900,000
	year 1000	$32,100,000	$32,100,000	$16,700,000	$6,400,000	$3,900,000	$200,000	$3,900,000
Change in cancers (from Option 1)	year 100		0.0	1.7	2.9	3.1	3.6	3.1
	year 250		0.0	4.3	7.1	7.9	8.9	7.9
	year 500		0.0	8.6	14.3	15.7	17.9	15.7
	year 1000		0.0	17.1	28.6	31.4	35.5	31.4
Cost for decrease in cancers	year 100		$0	$1,500,000	$2,600,000	$2,800,000	$3,200,000	$2,800,000
	year 250		$0	$3,900,000	$6,400,000	$7,100,000	$8,000,000	$7,100,000
	year 500		$0	$7,700,000	$12,900,000	$14,100,000	$16,100,000	$14,100,000
	year 1000		$0	$15,400,000	$25,700,000	$28,300,000	$32,000,000	$28,300,000
C/B ratio at	year 100		ERR	1.3	4.5	5.2	26.3	1.2
	year 250		ERR	0.5	1.8	2.0	10.5	0.5
	year 500		ERR	0.3	0.9	1.0	5.2	0.2
	year 1000		ERR	0.1	0.5	0.5	2.6	0.1

ERR = cost/benefit ratio infinite (money spent for no benefit)

Table 11 - Costs and Benefit (Radiation)

		Option						
		1	2	3	4	5	6	7
Cost of option		$0	$12,400,000	$2,000,000	$11,800,000	$14,500,000	$84,200,000	$3,300,000
Cancers	year 100	0.4	0.8	0.2	0.1	0.003	0.0	0.02
	year 250	1.0	2.1	0.5	0.2	0.007	0.0	0.04
	year 500	2.1	4.2	1.0	0.4	0.014	0.0	0.09
	year 1000	4.1	8.4	2.0	0.8	0.029	2.0E-04	0.17
Costs of cancers	year 100	$400,000	$800,000	$200,000	$100,000	$0	$0	$0
	year 250	$900,000	$1,900,000	$500,000	$200,000	$10,000	$0	$0
	year 500	$1,900,000	$3,800,000	$900,000	$400,000	$10,000	$0	$100,000
	year 1000	$3,700,000	$7,600,000	$1,800,000	$700,000	$30,000	$0	$200,000
Change in cancers (from Option 1)	year 100		-0.4	0.2	0.3	0.4	0.4	0.4
	year 250		-1.1	0.5	0.8	1.0	1.0	1.0
	year 500		-2.1	1.1	1.7	2.1	2.1	2.0
	year 1000		-4.3	2.1	3.3	4.1	4.1	4.0
Cost for decrease in cancers	year 100		($400,000)	$200,000	$300,000	$400,000	$400,000	$400,000
	year 250		($1,000,000)	$500,000	$700,000	$900,000	$900,000	$900,000
	year 500		($1,900,000)	$1,000,000	$1,500,000	$1,900,000	$1,900,000	$1,800,000
	year 1000		($3,900,000)	$1,900,000	$3,000,000	$3,700,000	$3,700,000	$3,600,000
C/B ratio at	year 100		-31.0	10.0	39.3	36.3	210.5	8.3
	year 250		-12.4	4.0	16.9	16.1	93.6	3.7
	year 500		-6.5	2.0	7.9	7.8	44.3	1.8
	year 1000		-3.2	1.1	3.9	3.9	22.8	0.9

Table 12 - Costs and Benefits (Combined Arsenic, Nickel and Radiation)

		Option						
		1	2	3	4	5	6	7
Cost of option		$0	$12,400,000	$2,000,000	$11,800,000	$14,500,000	$84,200,000	$3,300,000
Cancers	year 100	4.0	4.4	2.1	0.8	0.4	0.0	0.4
	year 250	10.0	11.0	5.1	2.0	1.1	0.0	1.1
	year 500	19.9	22.1	10.3	4.0	2.2	0.0	2.2
	year 1000	39.9	44.1	20.6	8.0	4.3	0.2	4.5
Costs of cancers	year 100	$3,600,000	$4,000,000	$1,900,000	$700,000	$400,000	$0	$400,000
	year 250	$9,000,000	$9,900,000	$4,600,000	$1,800,000	$1,000,000	$0	$1,000,000
	year 500	$17,900,000	$19,900,000	$9,300,000	$3,600,000	$1,900,000	$0	$2,000,000
	year 1000	$35,900,000	$39,700,000	$18,500,000	$7,200,000	$3,900,000	$200,000	$4,000,000
Change in cancers (from Option 1)	year 100		-0.4	1.9	3.2	3.6	4.0	3.5
	year 250		-1.1	4.8	8.0	8.9	10.0	8.9
	year 500		-2.1	9.6	15.9	17.8	19.9	17.7
	year 1000		-4.3	19.3	31.9	35.5	39.7	35.4
Cost for decrease in cancers	year 100		($400,000)	$1,700,000	$2,900,000	$3,200,000	$3,600,000	$3,200,000
	year 250		($1,000,000)	$4,300,000	$7,200,000	$8,000,000	$9,000,000	$8,000,000
	year 500		($1,900,000)	$8,700,000	$14,300,000	$16,000,000	$17,900,000	$15,900,000
	year 1000		($3,900,000)	$17,400,000	$28,700,000	$32,000,000	$35,700,000	$31,900,000
C/B ratio at	year 100		-31.0	1.2	4.1	4.5	23.4	1.0
	year 250		-12.4	0.5	1.6	1.8	9.4	0.4
	year 500		-6.5	0.2	0.8	0.9	4.7	0.2
	year 1000		-3.2	0.1	0.4	0.5	2.4	0.1

discounting, were used in the subsequent analysis. This analysis could be extended to include the regional and/or global population in a similar manner. In this case, the ranking of options would not be affected by a change in population group. Values, as total cancers for radiation exposure, arsenic and nickel exposure and the combined radiation, arsenic and nickel exposures are shown in Tables 10 to 12 respectively.

Note 1.4 In a decision problem where the "optimal" of a number of actions pertaining to the same problem are being considered, the absolute values of cost are not as relevant as in cases where the decision pertains to different uses of the same money (ie. hospital spending versus elevated railway crossings versus tailings site decommissioning). In the later case, a more objective value is required. In the current study, as long as each option is treated in a similar manner, (i.e. relative ratios between options are preserved), comparisons between options can still be made without distortion or error.

Step 2. Health Impact Conversion to Dollars

The International Commission on Radiological Protection recommends a value of between $10,000/man-Sv and $20,000/man-Sv (ICRP37). For the current study, an average value of $15,000/man-Sv was used.

In order to evaluate the dollar value of doses received from the non-radiological components (arsenic and nickel), it is necessary to develop a value consistent with the radiological dollar/dose value, in terms of dollar/man-gram. As there is no direct conversion from man-gram to dollars, cancers were used as a common unit. As discussed in section 4.3, for every 70 man-Sv (a lifetime at 1 man-Sv/a), 1.16 cancers are anticipated. On the basis of the $15,000/man-Sv, this equates to a value of $900,000/cancer.

Note 2.1 For interest, this converts into values of $7,100/man-gram and $3.5/man-gram for arsenic and nickel respectively.

The cost of the cancers for each option can then be readily calculated by multiplying the number of cancers by $900,000. This is shown in Tables 10 to 12, for arsenic and nickel induced cancers, radiation induced cancers and the combined cancers, respectively.

As well, the reduction in the number of cancers from the base case can be calculated for each option. This was done by subtracting the number of cancers for a given option at a given time from the base case (Option 1) cancers at the same time. These reductions are then converted to dollar values on the basis of $900,000/cancer. These results are also shown in Tables 10 to 12. This later value is the "benefit" of a particular option.

Data from Tables 10 to 12 are shown graphically in Figures 29 to 31 which show the comparative costs of cancers reduced and cost of the option for the arsenic and nickel, radiation and the combined arsenic, nickel and radiation at year 500. The "best" options are those where the cost of cancers reduced is greater than the cost of the option.

Step 3 - Calculate the Cost/Benefit Ratio

The cost/benefit ratio is calculated on the basis of dividing the option's cost by the dollar value of the benefit of cancer reduction. The results of these calculations are shown in Tables 10 to 12.

Step 4 Comparison of Options

In the case of uranium mill tailings decommissioning, the cost/benefit ratio has limited value in the ranking of options. As discussed in Chapter 3, the main purpose of the cost benefit ratio is for the assignment of fixed resources to different projects. In such a case, the lower the ratio, the better the choice. In the present example, this ratio can serve to choose between options with similar benefits and would, in a limited fashion, be similar to an incremental cost-effective analysis.

When the cost/benefit ratio is greater than 1, more money is being spent on

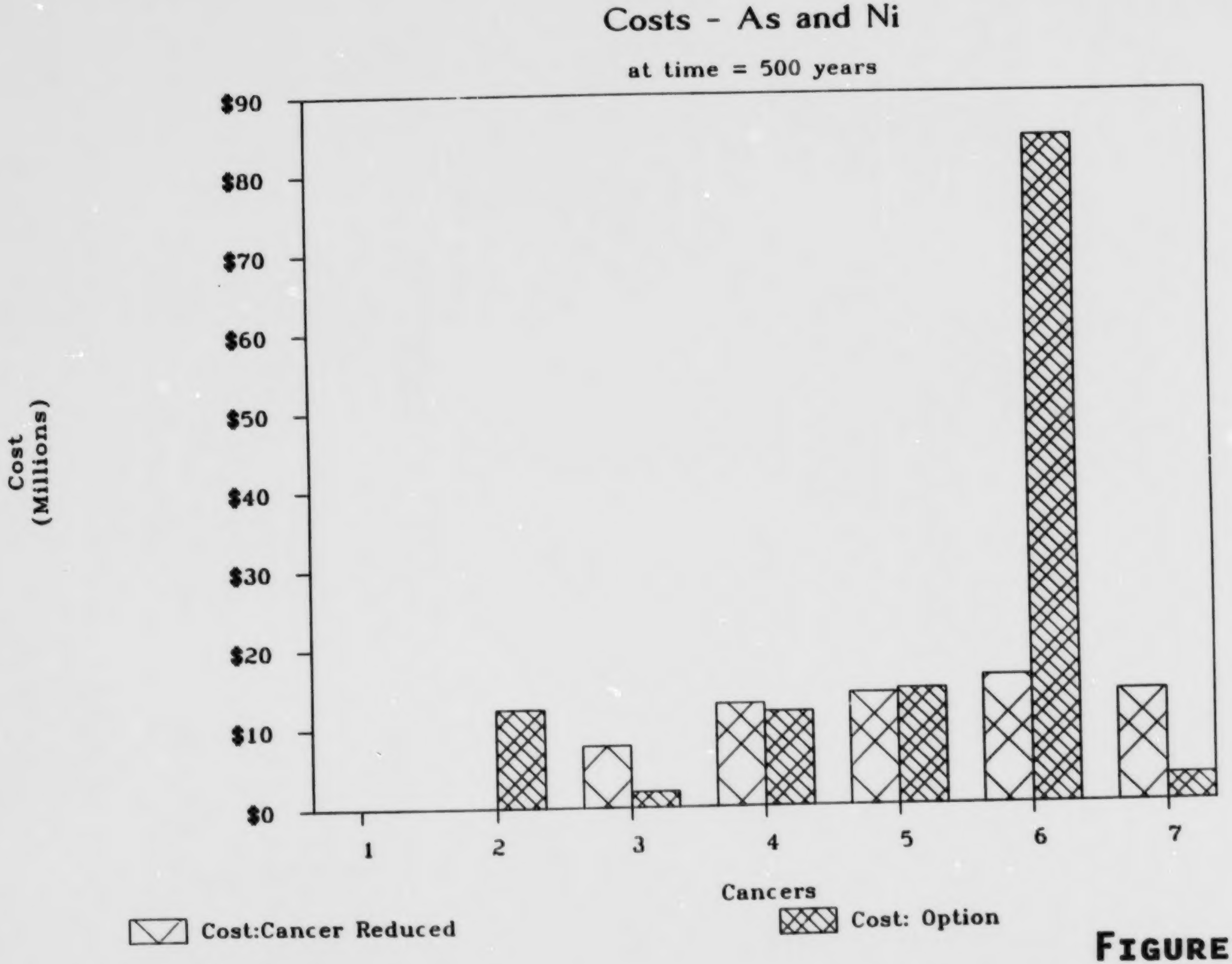

Costs - As and Ni
at time = 500 years
Cost
(Millions)
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
1
2
3
4
5
6
7
Cancers
Cost:Cancer Reduced
Cost: Option

FIGURE 29

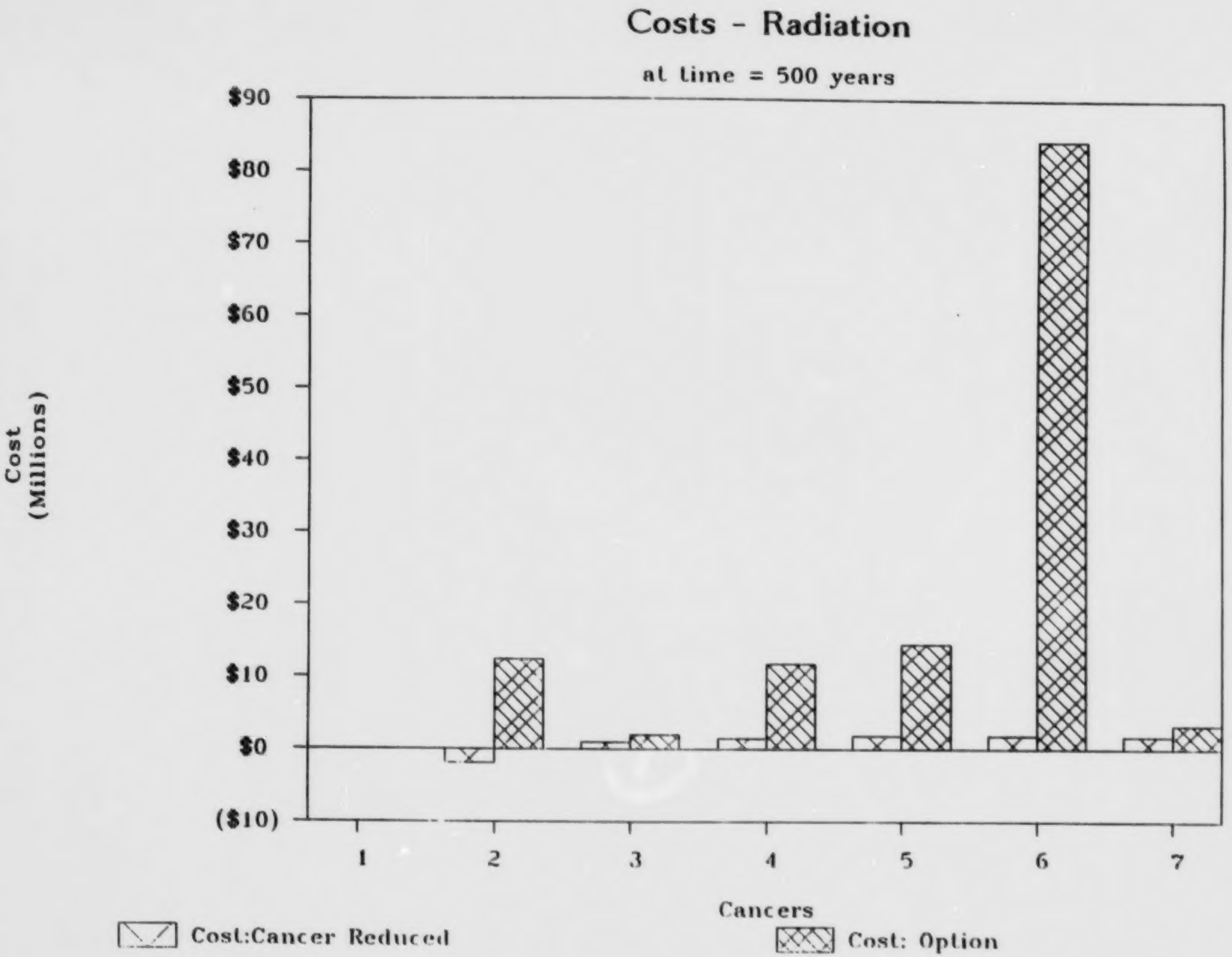

Costs - Radiation
at time = 500 years
Cost
(Millions)
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
($10)
1
2
3
4
5
6
7
Cancers
Cost:Cancer Reduced
Cost: Option

FIGURE 30

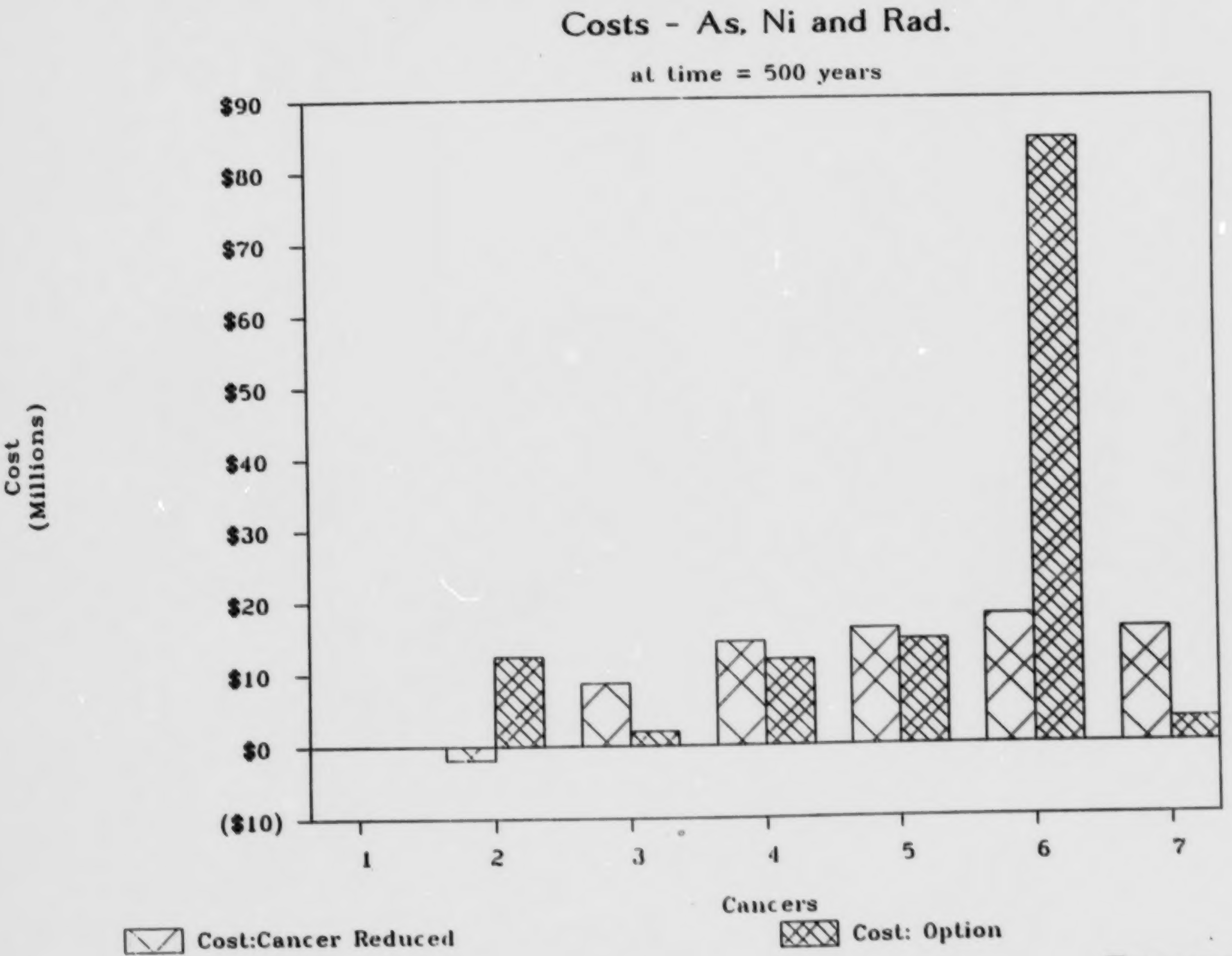

Costs - As. Ni and Rad.
at time = 500 years
Cost
(Millions)
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
($10)
1
2
3
4
5
6
7
Cancers
Cost:Cancer Reduced
Cost: Option

FIGURE 31

the remedial action than the savings brought about by reducing the health impact. At ratios less than 1, the cost spent on the remedial action is less than the value attributed to savings in health impacts. In other words, for comparative purposes, the lower the ratio, the better.

In the results presented in Table 10, the cost/benefit ratio for the combined arsenic and nickel exposure ranges from a level of infinity (indicated as an ERR on table), implying monies spent with no reduction in dose, to a low of 0.1 at year 1000. In the case of Option 6 (moving the tailings), the cost/benefit ratio is always greater than 1 (unless extrapolation of dose were to be continued past 1000 years). This implies that more monies are being spent on reduction of cancers, than the actual cancers cost. In this case the options would rank (best to worst) as 7, 3, 4, 5, 6 and 2.

Similar results are seen in Table 11, for the radiation induced effects. Here the ratios are higher, since the number of modelled radiation induced cancers is lower than the modelled arsenic and nickel induced cancers. In this case, very few of the ratios are less than one. This implies that the costs spent to reduce the radiation induced cancers are greater than the costs of the cancers (at $900,000/cancer). Option 2, in Table 11, has a negative ratio. This implies that monies are spent to increase concerns! This might be acceptable if other factors outway the increase. Again these ratios change if longer time integration were used or if the cost of cancers were considered to be higher. In this case the options would rank (best to worst) as 7, 3, 5, 4, 6 and 2.

Table 12 shows the results of the combined arsenic, nickel and radiation induced cancers. In this case, the ratios are reduced from the previous examples, since now all of the modelled cancers are included. The best cost/benefit is shown for option 7, with the rest ranked as 3, 4, 5, 6 and 2.

Note: This ranking, however, can be misleading without the performance of a cost-effective and marginal cost effectiveness analysis.

In effect, the latter scenario (Table 12, Figure 31), using all of the modelled cancers or reduction in modelled cancers is the most realistic for decision methods. The actual choice of the "optimal" solution depends upon the time horizon used. Objectively, none of these options yield a satisfactory cost/benefit ratio prior to 100 years. All of these ratios are greater than one. This implies that more would be paid to decommission the site, than would be accepted as the cost of reducing the number of cancers. As time progress, each option starts to become more acceptable on the basis of the ratio.

Note 4.1 If one were to discount cancers, the ratios calculated for the longer times would not decrease as rapidly as with no discounting. As "present value lives", lives after a long time would have no impact on the ratio, ie. the ratio would approach a minimum, which would be dependent upon the discounting rate used. Table 13 presents values for different discount rates. The values were determined on the basis of one cancer/year. For example, at year 250, with a discount rate of 0.005 the present value of the total cancers is 142.5. With no discounting, this would be 250. If discounting is used, the rate in effect determines an upper time limit for health impacts. In the example, (0.005), the maximum discounted cancers would be 200. This implies that cancers after year 1000 are not important today. For the current study, no discounting was assumed, and a time of 500 years was arbitrarily chosen as a reference time for comparing options.

The impact of other criteria on the ratio were not estimated in this study. The effect would depend on whether the impact was considered to be a benefit (eg. increased employment) or a cost (eg. decrease in tourism). In fact, the same criteria could be considered to be either a cost or a benefit depending on the method of measuring the performance of the option under that criteria (eg. increased employment or increased unemployment). Estimates of the monetary value of these criteria becomes increasingly difficult the less precise the metric for performance under that criteria is from a dollar value (e.g. effect on employment is relatively easier to

TABLE 13

Present Value for Various Times at Various Discount Rates
(Assumed annual cancer rate of 1/a)

	Discount Rate				
Time (yrs)	0.001	0.005	0.01	0.05	0.1
10	9.9	9.7	9.5	7.7	6.1
100	95.1	78.5	63.0	19.8	10.0
250	221.1	142.5	91.7	20.0	10.0
500	393.3	183.5	99.3	20.0	10.0
750	527.5	195.3	99.9	20.0	10.0
1000	631.9	198.6	100.0	20.0	10.0
2500	917.8	200.0	100.0	20.0	10.0
5000	993.2	200.0	100.0	20.0	10.0
7500	999.4	200.0	100.0	20.0	10.0
10000	1000.0	200.0	100.0	20.0	10.0

assign a dollar value to than public acceptance).

It should be stressed at this point that ranking of options on the basis of cost/benefit ratios is only of limited value. Cost/benefit analysis is of particular strength in comparing dissimilar projects with differing costs and benefits. The cost/benefit ratio is then an effective indicator of whether or not the monies are well spent. In cases where a choice of similar actions is required, cost-effectiveness ratios are more useful in ranking options. As well, in both methods, the "no-action" option (option 1) cannot be properly ranked, as there is no cost (as defined) or benefit (as defined). This type of analysis is suited to situations where there is a desire or need to change the current situation. Cost-benefit and cost-effectiveness are then useful in deciding how best to use the monies.

5.3 Cost-Effectiveness

5.3.1 Overview

Unlike the cost-benefit procedure outlined in Section 5.1, there is no common unit needed for comparing dissimilar criteria but they can only be compared in pairs. For the current study, the cost-effectiveness of each option is considered on the basis of dollars for residual cancers and for reduction in cancers.

The overview of the procedure is:

1. Compile the total, discounted cost for each option. Compile the cumulative doses or cancers for each option.

2. Plot the cost versus residual cancers and compare the effectiveness of each option. Eliminate those options which are clearly "dominated", to

form a subset of the "best" options.

3. From the subset of "best" options, calculate the marginal cost-effectiveness.

4. Rank the options.

5.3.2 Details of Main Steps

Step 1 - Compile cost and health impact data

This procedure is similar to the compilation of data for the cost-benefit analysis. The reader is referred to Step 1 of the cost-benefit analysis for a discussion of the origin of cost and cancer data. The data is presented in Tables 14 to 16 for arsenic and nickel, radiation and arsenic and nickel and radiation respectively.

Step 2 - Plot of the Cost vs. Cancer Data

The data are plotted in Figures 32 to 34 at year 500, for the arsenic and nickel, radiation and the combined arsenic and nickel and radiation cancers. From these plots, it is possible to eliminate the dominated options. The procedure for determining the dominated options, involves connecting the options in such a manner as to define the lowest concave-upward envelope. This is shown as a solid line in Figures 32-34. Those options the exist off the line (and by following the correct procedure, always above the line) are clearly dominated by the other options. For example, in Figure 33, option 4 is clearly dominated by the other options. In other words, there are more cost-effective options than option 4, that are both cheaper and cause less cancers.

Table 14 - Cost - Effectiveness (Arsenic and Nickel)

		Option 1	2	3	4	5	6	7
Cost of Option		$0	$12,400,000	$2,000,000	$11,800,000	$14,500,000	$84,200,000	$3,300,000
Cancers	year 100	3.6	3.6	1.9	0.7	0.4	0.0	0.4
	year 250	8.9	8.9	4.6	1.8	1.1	0.0	1.1
	year 500	17.9	17.9	9.3	3.6	2.1	0.0	2.1
	year 1000	35.7	35.7	18.6	7.1	4.3	0.2	4.3

		Change between Options from 1 to 3	from 3 to 7	from 7 to 6
decrease in cancers	year 100	1.7	1.4	0.4
	year 250	4.3	3.6	1.1
	year 500	8.6	7.1	2.1
	year 1000	17.1	14.3	4.1
$/decrease in cancers	year 100	$1,200,000	$900,000	$188,800,000
	year 250	$500,000	$400,000	$75,500,000
	year 500	$200,000	$200,000	$37,800,000
	year 1000	$100,000	$100,000	$19,800,000

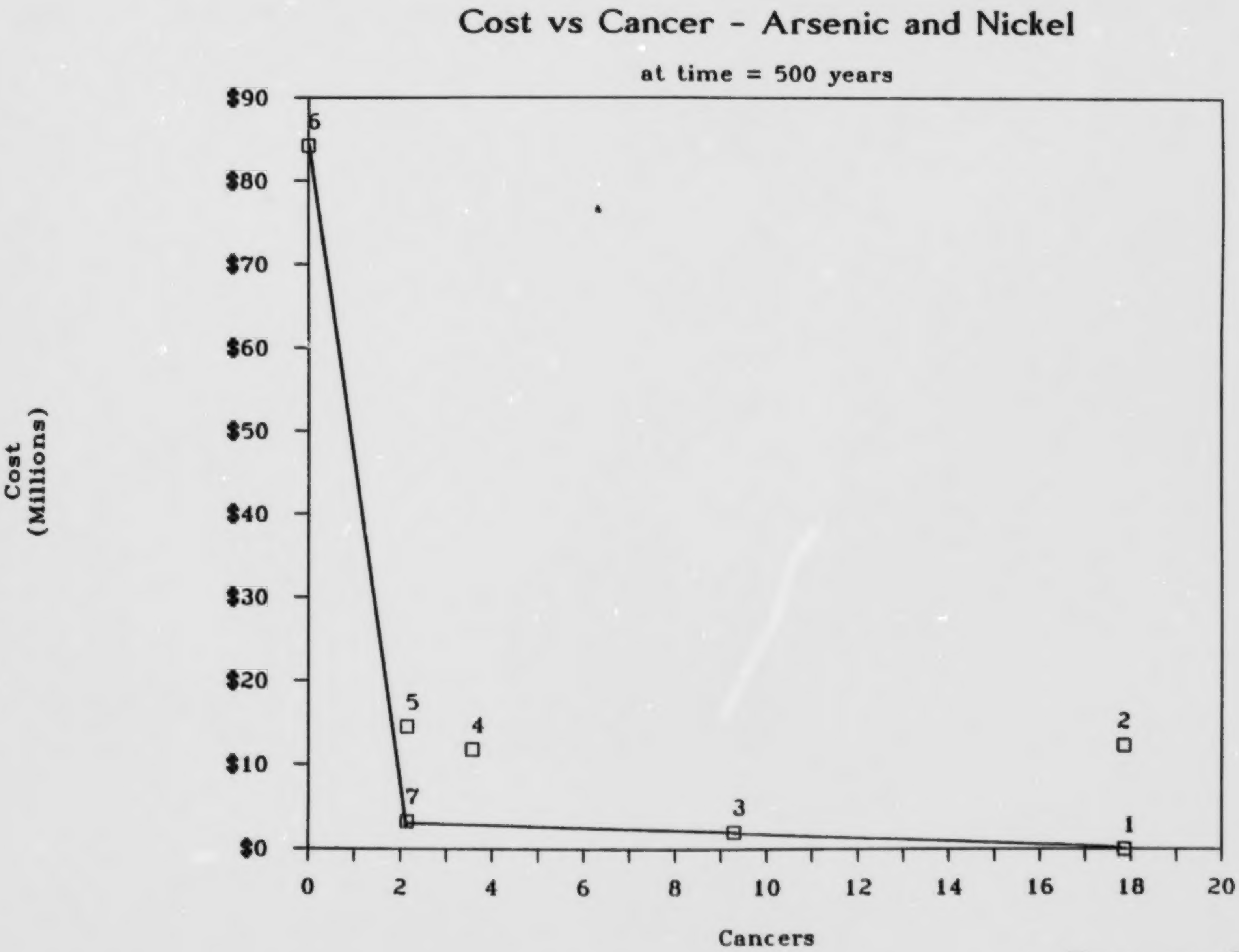

Cost vs Cancer - Arsenic and Nickel
at time = 500 years
Cost
(Millions)
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
0
2
4
6
8
10
12
14
16
18
20
Cancers
6
5
4
7
3
2
1

FIGURE 32

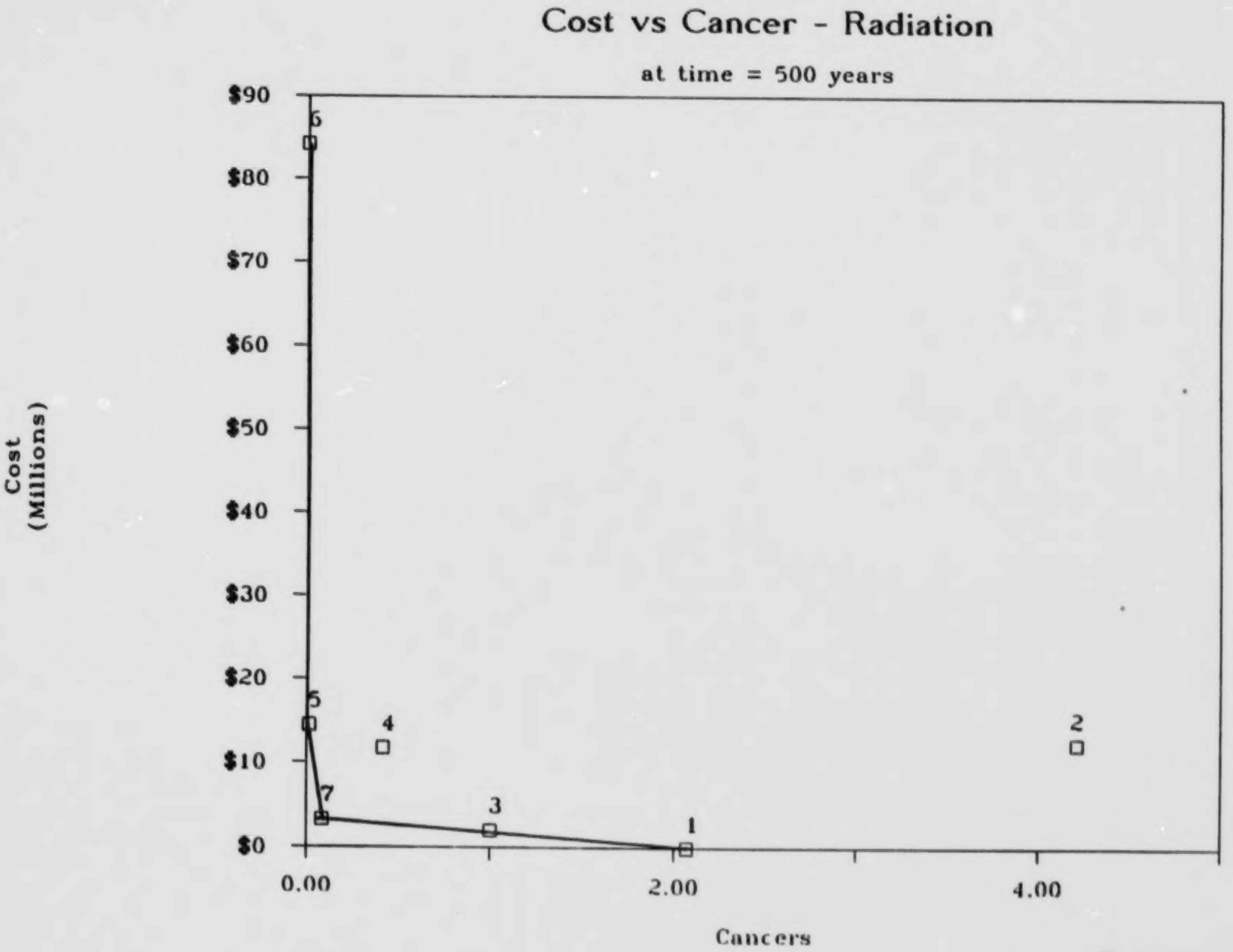

Cost vs Cancer - Radiation
at time = 500 years
Cost
(Millions)
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
0.00
2.00
4.00
Cancers
6
5
4
7
3
1
2

FIGURE 33

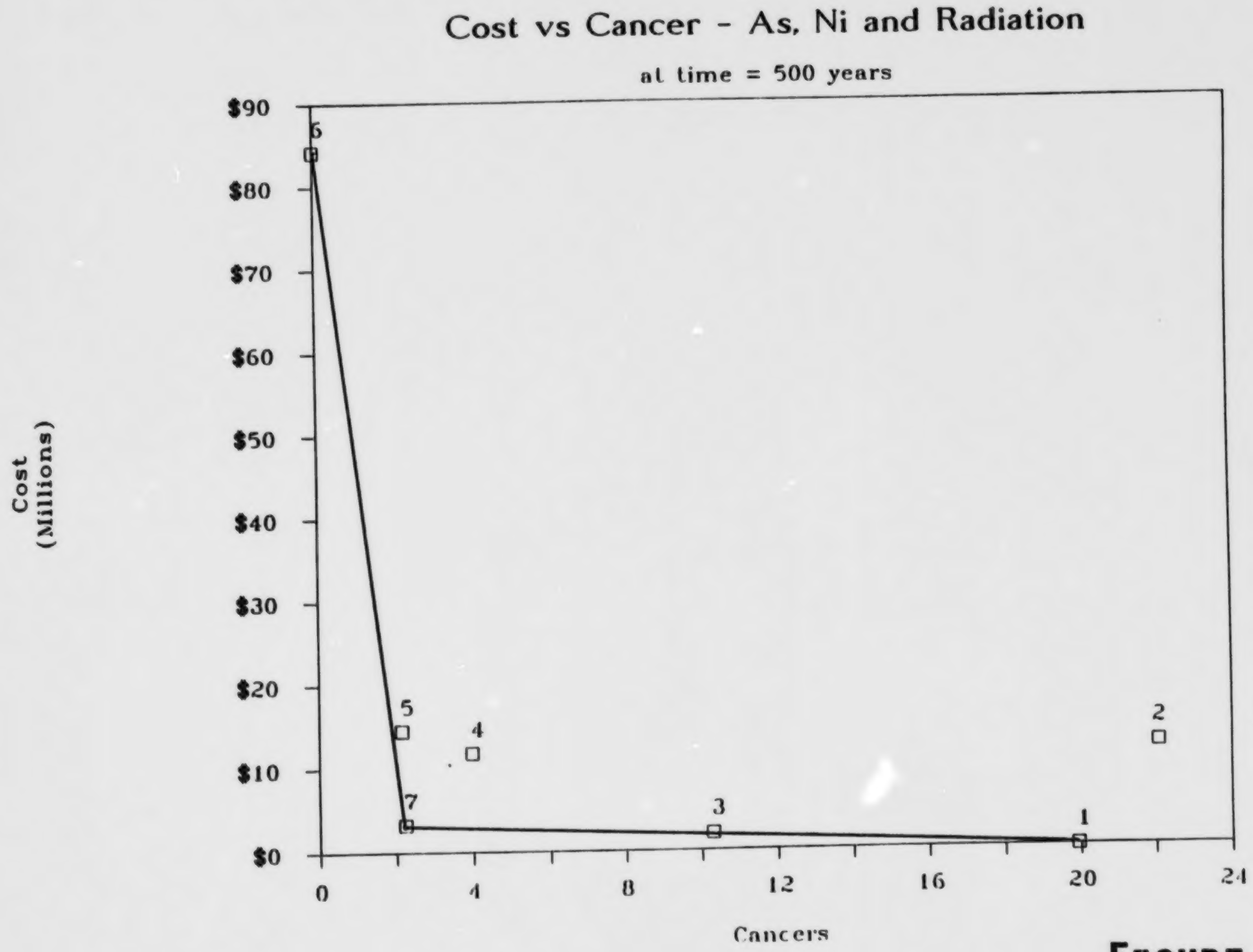

Cost vs Cancer - As, Ni and Radiation
at time = 500 years
Cost (Millions)
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
0
4
8
12
16
20
24
Cancers
6
5
4
7
3
1
2

FIGURE 34

Options 2 and 4 are dominated in all three figures, while 5 is marginally dominated in Figures 32 and 34.

From Figure 34, the "best" subset of options contains options 3, 5, 7 and 6. Other options are dominated. Option 5 is maintained since it is very close to the "optional" line.

Step 3 - Marginal Cost-Effectiveness

On the basis of the "best" of the nondominated subset, the marginal cost-effectiveness is calculated based on the incremental cost divided by the incremental cancers. This is just the slopes of the lines joining the nondominated options in Figures 32-34. This is performed as one moves to lower cancer levels, e.g. in Table 14 from 1 to 3, from 3 to 7 and from 7 to 6.

For interest and comparison the marginal cost-effectiveness for the radiation cancers and for As and Ni are also shown in Tables 14 and 15 respectively.

Step 4 - Comparison of Cost-Effectiveness Results

On the basis of the marginal cost-effectiveness, it is seen that in spending money to move from Option 1 to Option 3, results comparatively low costs for the decrease in cancers. Marginally (i.e. for the next dollars spent), the cost remains about the same in going from options 3 to 7, and becomes extremely costly in going from option 7 to 6.

On the basis of combined cancers, the options would be ranked (best to worst) by cost-effectiveness as 3 and 7 then 6. Another way of stating this conclusion, is that the extra dollars spent in going from 1 to 3 to 7 (or directly 1 to 7) result in approximately equivalent costs for cancers reduced.

Spending the monies for option 6, on the other hand, would, for the extra monies required, beyond the cost of option 7, only provide a comparitively marginal decrease in cancers.

5.4 Multi-Attribute Utility Theory

5.4.1 Overview

As discussed in Section 3, Multiattribute Utility Theory, allows the decision maker to consider numerous criteria. Detailed procedures abound in the literature for performing a MAUT analysis. The following outline is a synthesis of many of these procedures. Where applicable, alternate methods or procedures will be indicated in the notes. Option 6 has been omitted since its costs are totally out of line with the costs for other options.

In Section 4, the various options were compared on the basis of a non-exclusive set of criteria (Figure 4). For the purposes of the current example only a subset of mutually exclusive criteria were used. More could be added, but would add only to the extent of the calculations, not to the understanding of the method. As well, as will be demonstrated subsequently, only a few of the important criteria impact on the ranking of the options.

As discussed in Section 2, there is great flexibility in the details of the health impact effects. One method of looking at Figure 4, is to model and aggregate from the bottom of the health effects until a point is reached at which a subjective decision on combination is required. The level at which the judgement is required would be evaluated as separate criteria. For example, if the decision maker considers radiological impacts to be significantly different from non-radiological impacts, the performance for each option would be aggregated to give a radiological and non-radiological split. This is the situation shown in Figure 4. On the other hand, another decision maker might argue that occupational versus non-occupational cancers are more important. In such a case, the effects would be aggregated until they are split between occupational and public effects. These two cases are discussed in the following example as Case I and Case II respectively.

For these cases the following criteria are used;

Case I

Criteria 1 - Effect on Aquatic Wildlife

Criteria 2 - Local employment

Criteria 3 - Public acceptability

Criteria 4 - Institutional Control

Criteria 5 - Aesthetics

Criteria 6 - Flexibility to cope with future change

Criteria 7 - Cost

Criteria 8 - Non-radiological health impacts

Criteria 9 - Radiological health impacts

Case II

Criteria 1-7 - (as defined above)

Criteria 8 - Occupation health impacts

Criteria 9 - Public health impacts

The following is an outline of the steps required for an MAUT analysis;

1. Assignment of performance of each option under each criteria. Step 1, may or may not be done during the actual MAUT process. In some cases, specialists will be used to define the performance for each option. This is especially true for those criteria, such as aesthetics, where a judgmental appraisal is required. For other criteria, such as cost, the performance can either be modelled or assigned judgmentally.

2. Present the decision maker(s) with a clear description of each criterion. This should not only detail what is included but what is not included in the criteria. This latter process is to ensure that the criteria are mutually exclusive and no double counting of effects will occur.

   It is also important at this step to ensure that the decision maker understands the magnitude and range of each criterion. This latter aspect is important in the assignment of the weights for each criterion.

3. Rank the criteria.

4. For each pair of criteria (in ranked order), assign a number between 0 and 1 expressing the relative importance of the each criteria (paired comparison).

5. Calculate the relative importance of the ranked criteria.

6. Normalize the weights for each criterion.

7. Multiply the performance under each criterion by the weight for that criterion for each option.

8. Compare the options.

5.4.2 Detailed Procedure

Step 1 - Assignment of Performance under Criteria

For each criterion and for each option, it is necessary to evaluate the performance of that option for that criterion. Any consistent scale is usable (say 0 to 1, or 1 to 10 or 1 to 100). Care must be taken that for each criterion the scale exhibits the same characteristics (eg. 10 is always the best). For the current example, a scale of 1 to 10, with 10 being the best was established.

For criteria, such as health effects, the modelled cancers are scaled to fit a range of 1 to 10, with 10 being the best performance among the options, with performances of the other options scaled down from there on a ratio basis. For example, if one option has 10 cancers and a second option 20 cancers, then the first option would be given a rank of 10 and the second a rank of 10/20 of 10 or 5. Similarly for cost, the options are ranked from 10 (lowest cost) down to the highest cost.

Other criteria can be assigned performance scores either on the basis of modelling (eg. economic modelling for employment etc) or on the judgement of experts. For Cases I and II, the performances under each criterion are shown in Tables 17 and 18. These values were determined on the basis of the scales developed in Section 4. These should be considered as based on expert judgement (as opposed to objective modelling) so are subjective and not an expression of values.

Note 1.2 In many cases each specialist will develop a different set of performance numbers. Methods, such as

- pessimistic ie. picking the worst performance for that option and criteria;

Table 17 Performance Under the Criteria for Case I

Criterion	Option 1	Option 2	Option 3	Option 4	Option 5	Option 7
1	1.2	2.5	5	7.5	10	8.7
2	1	3	3	5	6	10
3	1.2	2.5	7.5	8.75	10	2.5
4	6.3	6.3	6.3	10	10	1.25
5	1.25	1.25	7.5	10	10	1.25
6	8	8	8	4	3	10
7	10	1.5	8.6	1.9	1	7.7
8	1	1	5.9	9.2	10	10
9	5.6	1	7.9	9.1	10	9.8

Table 18 Performance Under the Criteria for Case II

Criterion	Option 1	Option 2	Option 3	Option 4	Option 5	Option 7
1	1.2	2.5	5	7.5	10	8.7
2	1	3	3	5	6	10
3	1.2	2.5	7.5	8.75	10	2.5
4	6.3	6.3	6.3	10	10	1.25
5	1.25	1.25	7.5	10	10	1.25
6	8	8	8	4	3	10
7	10	1.5	8.6	1.9	1	7.7
8	10	8	9	3	3	1
9	1.2	1	7.3	9.2	10	9.9

- optimistic ie. picking the best performance for that option and criteria;

- averaging ie. averaging all of the performances for that option and criteria;

have been used in numerous studies. In the decommissioning problem, where opinions are expected to be very diverse, the pessimistic approach will usually be the most useful as it will give full weight to the most severe opinion of the experts.

Step 2 Presentation of the Criteria

It is essential in a MAUT analysis that the criteria be mutually exclusive, ie. no overlap. As the decision maker evaluates the performance under the criteria (Step 1) an understanding of the various criteria is developed. At this Step, it is necessary to specify what is and what is not included in the criteria.

For example, in the public acceptability criterion, it is essential that the decision maker understand that this must not include the effect on local employment. If this is not possible, ie the decision maker cannot separate the criteria, it is best at this stage to redefine or modify the set of criteria and revaluate the performance (i.e. return to Step 1).

Note 2.1 In the literature, Keeney (see numerous references under Keeney in the Bibliography) details an involved question and answer procedure to ensure that the criteria are mutually exclusive. This procedure is recommended if the decision maker cannot be convinced by description alone, of the independence of the criteria.

As well, at this point of the procedure, the decision maker should be made aware of the ranges of the various criteria. This is essential for the next step, ranking and weight assignment.

Step 3 - Ranking of Criteria

At this point in the procedure, the decision maker is asked to rank the criteria on the basis of the range of impacts, using the worst case, and based on the information in step 2. These are listed as most important first.

This was done by our "decision maker" and the results are shown in Tables 19 and 20 for Case I and II respectively.

Step 4 - Paired Comparison of Criteria

Each pair of criteria is taken, and a weight between 0 and 1 assigned to the relative importance the decision maker places upon the two criteria. For example in Case I (Table 19), Criteria 8 and 9 where considered to be of equal weight, and Criteria 7 was considered to be 0.8 as important as Criteria 4. This process is repeated for all of the ranked criteria.

Results of our "decision maker" are shown in Tables 19 and 20.

Step 5 - Calculate the Relative Importance of Criteria

On the basis of the paired weights, the relative weights for each criteria are calculated. This is done by setting the first criteria weight equal to 1 and multiplying by the paired weight. As each weight is calculated, it is used with the next set of paired weights to calculate the next relative weight. In case I, for example, Criteria 7 has a relative weight of 0.8 and a paired weight (with Criteria 3) of 0.6. This results in a relative weight for Criteria 3 of 0.48 (0.8 * 0.6).

The relative weights for Case I and Case II are presented in Tables 19 and 20 respectively.

Table 19 - Case I - Assignment and Evaluation of Weights

Criterion Rank	Pair Weight	Relative Weight	Normalized Weight
8		1	0.214
	1		
9		1	0.214
	1		
4		1	0.214
	0.8		
7		0.8	0.171
	0.6		
3		0.48	0.103
	0.4		
2		0.192	0.041
	0.5		
6		0.096	0.021
	0.9		
1		0.0864	0.018
	0.2		
5		0.01728	0.004

Table 20 - Case II - Assignment and Evaluation of Weights

Criterion Rank	Pair Weight	Relative Weight	Normalized Weight
9		1	0.27019
	1		
4		1	0.27019
	0.8		
7		0.8	0.21615
	0.4		
8		0.32	0.08646
	1		
3		0.32	0.08646
	0.4		
2		0.128	0.03458
	0.5		
6		0.064	0.01729
	0.9		
1		0.0576	0.01556
	0.2		
5		0.01152	0.00311

Step 6 - Normalize the Weights

The relative weights are normalized to a sum of one. This is done by dividing each relative weight by the sum of all of the relative weights. This allows future relative intercomparisons between weights and rankings. On a single decision maker basis, normalizing weights is not important in the final ranking of options.

The results for the current decision maker are shown in Tables 19 and 20, for Cases I and II respectively.

Note 6.1 In cases where there are multiple decision makers, techniques exist for combining the weights of the set of decision makers. Methods, such as

- high weighting ie. picking the highest weight for that criteria (someone thinks it is very important);
- low weighting ie. picking the lowest weight for that criteria (no one thought it less important than the lowest weight);
- averaging ie. averaging all of the weights for that criteria (balancing those who think criteria highly important and less important);

have been used in numerous studies. In the decommissioning problem, where opinions are expected to be very diverse, the high weighting approach will usually be the most useful between groups of decision makers, as it will give full weight to the most severe opinion. Within a group of decision makers with a fairly consistent position (for example, an opposition group) averaging of the weights is recommended to develop a consensus stand or set of weights for that group's opinion.

Step 7 - Calculate the Weighted Performance for each Option under each Criteria

For each option and each criteria, the normalized weight for that criteria is multiplied by the performance under that criteria. For example, in Case I, Criteria 4 has a weight of 0.21. For option 1, the performance under Criteria 4 is 6.3 (Table 17). Therefore the weighted performance for Criteria 4 for option 1 is 1.35 (0.21*6.3). This is repeated for all options and all criteria.

The results for the current study are shown in Tables 21 to 22.

Step 8 - Comparison of Options

Numerous methods exist for comparing the options, once the weighted performance has been determined. The two examined here are summation (highest score being preferred) and max-min (ie ranked on the basis of the highest minimum scores). The results for the current example are shown in Tables 20 and 21.

On the basis of the summed weights, the options rank from best to worst as follows;

Case I

5 - 4 - 3 - 7 - 1 - 2

Case II

3 - 5 - 4 - 7 - 1 - 2

On the basis of max-min, the options rank as follows;

Table 21 Weighted Performance Under the Criteria for Case I

Criterion	Option 1	Option 2	Option 3	Option 4	Option 5	Option 7
1	0.02	0.05	0.09	0.14	0.18	0.16
2	0.04	0.12	0.12	0.21	0.25	0.41
3	0.12	0.26	0.77	0.90	1.03	0.26
4	1.35	1.35	1.35	2.14	2.14	0.27
5	0.00	0.00	0.03	0.04	0.04	0.00
6	0.16	0.16	0.16	0.08	0.06	0.21
7	1.71	0.26	1.47	0.33	0.17	1.32
8	0.21	0.21	1.26	1.97	2.14	2.14
9	1.20	0.21	1.69	1.95	2.14	2.10
	-----	-----	-----	-----	-----	-----
Sum	4.83	2.63	6.95	7.75	8.15	6.86
Min	0.005	0.005	0.028	0.037	0.037	0.005

Table 22 Weighted Performance Under the Criteria for Case II

Criterion	Option 1	Option 2	Option 3	Option 4	Option 5	Option 7
1	0.02	0.04	0.08	0.12	0.16	0.14
2	0.03	0.10	0.10	0.17	0.21	0.35
3	0.10	0.22	0.65	0.76	0.86	0.22
4	1.70	1.70	1.70	2.70	2.70	0.34
5	0.00	0.00	0.02	0.03	0.03	0.00
6	0.14	0.14	0.14	0.07	0.05	0.17
7	2.16	0.32	1.86	0.41	0.22	1.66
8	0.86	0.69	0.78	0.26	0.26	0.09
9	0.32	0.27	1.97	2.49	2.70	2.67
Sum	5.35	3.49	7.30	7.00	7.19	5.64
Min	0.0039	0.0039	0.0233	0.0311	0.0311	0.0039

Case I

(4 - 5) - 3 - (7 - 1 - 2)

Case II

(4 - 5) - 3 - (7 - 1 - 2)

(bracketed options are considered equivalent)

In it interesting to note that the ranking, based on summation of weights, changed when the health impacts were separated on the basis of radiation vs arsenic and nickel effects and public vs occupational effects.

The ranking of options can be quite different for MAUT than for cost-benefit or cost-effectiveness because many criteria besides cost and health effects can be considered.

5.5 Decision System

5.5.1 Overview

The decision system, as envisioned for use in the tailings decommissioning problem, entails a recursive procedure, aimed at resolving differences in position. Unlike the previous methods, which are frequently used to "pick the option" which translates to "make the decision", the decision system makes use of the above methods as flexible tools. Often the previously discussed methods are used as an inflexible "objective" decision process. There might be some discussion on the weights and performance of the options, but in effect the ultimate result of the method (be it cost-benefit, cost-effectiveness or MAUT) are considered to be the "optimal" solution within the context of the methods.

The decision system approach departs from this rigid structure and allows a process with much more flexibility and avenues for discussion. The intermediate result of such a process allows for the ultimate definition or exposure of the true basis upon which different decision makers are at fundemental odds. Having uncovered this difference, classical methods of resolving conflict (for example - compensation) can be used to modify the options and arrive at a mutually agreeable "optimal" solution.

The decision process can be viewed as a series of "rounds". These rounds would utilize a number of the various procedures discussed previously, depending upon the criteria considered important by all decision makers. Cost-effectiveness and MAUT become very useful tools in discussing and resolving conflicts within these rounds.

5.5.2 Detailed Example of Decision System

The following is but an example of how a decision system might be used and how it would progress through a series of rounds between a group responsible for the decommissioning and a group representing the public opinion. Though the following discussion might appear to be a bit more vague than previous sections, it should be remembered that the previous procedures are inherent in the decision system. Rather than repeating the details of the already discussed methods, they will only be refered to by procedure and the user should employ the step-by-step procedure outlined in the relevant sections.

Preliminary to Round 1

Each group would formulate a number of options for decommissioning the tailings. These would be on a descriptive basis with some discussion on the merits of the option.

As well, each group would develop a set of criteria, which would be considered important to them. These need not be ranked or even justified at this stage.

Round 1

The groups would meet and options and criteria exchanged. This is in essence the preliminary screening of all tailings decommissioning options. During this session a list of viable options and relevant criteria would be developed. These would be used as the basis for further study.

Between Rounds 1 and 2

Modelling would be performed to evaluate the performance of the options under the various criteria. Specifically, risk and cost modelling would be done. For the other criteria, some preliminary assessment as to their performance should be undertaken. A cost-effectiveness (or cost-benefit) analysis can be undertaken to compare the options on the basis of cost and health impacts.

Round 2

The results of the modelling and assessment are discussed. Data used in the models or in extreme cases revised models are agreed upon, if there is no consensus of the modelling results. The number of options might be reduced on the basis of cost-effectiveness. In our example, Option 6 would be rejected on the basis of excessively high marginal cost-effectiveness, leaving the remaining options for further study.

Since these are agreed upon by both groups, the next step involves the evaluation of the other criteria. This procedure is discussed in the MAUT procedure. Weights are also assigned to each criteria.

Between Rounds

On the basis of the agreed upon criteria, the performance of the various options is evaluated. The evaluation of the various options is performed on the basis of assigned weights. These are summarized by a number methods (summation, min-max etc) and the results presented at the next round.

Round 3

The ranking of the options, and the weighted performance under the various criteria are considered by each group. If there is some disagreement, weights or performance can be changed to reconcile the groups differences. In our example, options 3, 4 and 5 were found to be relatively close in preference. It would then be possible to examine these options in greater detail for, say a reduced set of important criteria. More modelling might be required.

Between Rounds

The new performance under each criterion is developed.
These are shown in Table 23. (Case I only.)

Round 4

On the basis of the new range of performance values, new weights can be assigned to the criteria. The options are then re-evalutated to obtain new MAUT aggregate scores. In our current session, the result of the new weights and the new weighted performances are shown in Tables 24 and 25. In our hypothetical rounds, the "optimal" option was agreed upon as being Option 4 with Option 5 being a close second.

In a case where the conflict continues, conflict resolution techniques (not part of the scope of the current study) would be utilized to resolve the difference for a specific criterion. For example, some modification might be made to the Option to resolve the concern over, say aesthetics, or in

Table 23 - Performance Under the Criteria
Reduced Options

Criterion	Option 3	Option 4	Option 5
1	1	5	10
2	2	5	10
3	1	5	10
4	3	10	10
5	6	10	10
6	10	6	1
7	10	2	1
8	7.5	10	2.9
9	1	5	10

Table 24 - Case I - Assignment and Evaluation of Weights
Reduced Options

Criterion Rank	Pair Weight	Relative Weight	Normalized Weight
9		1.0000	0.3821
	0.8		
8		0.8000	0.3057
	0.8		
7		0.6400	0.2445
	0.1		
3		0.0640	0.0245
	1		
2		0.0640	0.0245
	0.3		
1		0.0192	0.0073
	0.8		
6		0.0154	0.0059
	0.5		
5		0.0077	0.0029
	0.9		
4		0.0069	0.0026

Table 25 - Weighted Performance Under the Criteria
Reduced Options

Criterion	Option 3	Option 4	Option 5
1	0.01	0.04	0.07
2	0.05	0.12	0.24
3	0.02	0.12	0.24
4	0.01	0.03	0.03
5	0.02	0.03	0.03
6	0.06	0.04	0.01
7	2.45	0.49	0.24
8	2.29	3.06	0.89
9	0.38	1.91	3.82
Sum	5.28	5.83	5.58
Min	0.01	0.03	0.01

more extreme cases, some form of compensation (eg. a committment to a research centre to compensate for lose of local employment).

6.0 CONCLUSIONS AND RECOMMENDATIONS

- The techniques discussed in this study were used to evaluate a simple set of scenarios and options. The most realistic procedure was found to be the decision system procedure incorporating models to focus the worth of the options more clearly. Though in many respects less structured than a single, once-through procedure, it is far more flexible in its ability to cope with differences in opinion and focussing the decision process on the most important criteria and most relevant options. This procedure formalizes the actual procedure that is followed in a real decision process (real as opposed to the current study being a hypothetical example).

- Other procedures, such as cost-benefit, cost-effectiveness and MAUT are limited if used as a stand alone and single pass system. Though these methods can all be extended to cover many criteria (eg. the cost of aesthetics can be determined), these extensions can lead to numerous areas of conflict (eg. cost of human life). This type of conflict is not productive. In the decision system, each of these methods is used for its area of greatest strength (eg. cost-effectiveness in determining the costs involved in saving cancers or reducing doses, MAUT comparing dissimilar criteria).

- It is recommended that the decision system be attempted on a simulated real situation, with a number of volunteer groups representing various positions.

- It is recommended that the use of simple computer algorithms to quickly evaluate cost-effectiveness and perform a MAUT analysis, be investigated. These algorithms would allow the actual mechanics of the procedures to be repeated rapidly and expand the ability to examine a number of decision makers positions and the effects on the choice of the optimal decommissioning option. The common term for such systems is "decision support" systems.

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APPENDIX I

DISPOSAL OPTIONS AND JUDGEMENTS ABOUT THE FUTURE

Prepared for MacLaren Plansearch, by R.V. Osborne 86-12-01

The main thesis in this essay is that it is unnecessary to consider truncation in either space or time of estimates of individual or collective doses in deciding, from the point of view of radiaiton protection, which method of disposing of tailings is most acceptable. It can be accepted that uncertainties in estimates of the differences in future and distant doses that arise with different options for disposal are great. A decision between such options is therefore fairly insensitive to such comparisons. As a result, "truncation" is not an issue but can be seen as an "unnecessary" extreme form of weighting contributary factors in a multiattribute analysis that is designed to help to select the best option.

The question of truncation in space and time usually arises in connection with estimates of collective dose commitment when some kind of comparative analysis is being considered using collective dose commitment as a measure of impact on health (1).

If we estimate, using available environmental models, the collective dose commitment from a particular radioactive waste disposal facility we may observe one or more of the following characteristics in our estimate.

(1) A substantial part of the dose is received by individuals at a very long time in the future (i.e. thousands, millions of years hence).
(2) There are very large error bars on the estimate of collection dose.
(3) A substantial part of the collective dose is received at very low individual dose rates (i.e. less than a few μSv/a).
(4) A substantial part of the collective dose is received by people outside the country in which the facility is sited.

The issues that arise are discussed in the following five sections. The final section summarizes how the NEA and ICRP have approached the problem.

Collective doses in the future

One argument is that the detriment to health occurring in the far future should be valued less than detriment in the near future. This different valuation is independent of the certainty with which we can estimate collective dose commitments. Some form of discounting has been suggested, e.g. an exponential decrease in value with time. Economic arguments have been presented to support this though not very convincingly. Alternatively, more pragmatic reasons have been presented to support the simple truncation of the time over which collective dose needs to be considered. One is simply that it is unreasonable to expect to have responsibility for civilizations many thousands of years in the future. For surface facilities, there is also the argument that the need for repairs to containment after, say, a few hundred years, could far more easily and cheaply be met at that time than by trying to ensure now that containment could be effective for many thousands of years.

Uncertain collective doses

In many instances these issues are related to time as well. With long-lived radioactive waste, engineered controls over the containment of the waste cannot be guaranteed over the times long compared with the half-lives of some of the radionuclides. There will therefore be an increasing uncertainty in the predicted release rates from a waste facility with increasing time. Distribution of the released waste over very long times results in a global distribution that cannot be predicted very accurately for several reasons. We may not have adequate models or appropriate parameters for the longterm processes involved, and there may be changes in the environment - from climatic changes for example - or in population size, distribution, and habits. In many instances, estimating what the uncertainties are (i.e. the "error bars" on the estimates of collective dose) is difficult.

As a consequence of such uncertainties it may be that no significant difference can be predicted in the estimates of collective doses for many options for managing a particular kind of waste. What this means, simply, is that the preferred option may be chosen on some other basis. Suppose for example, only a cost-benefit analysis were to be used as the "decision-aiding" tool in determining which of several disposal facilities would be the optimum. Because of modelling uncertainties the benefits from increased expenditures are not apparent. Then the optimum would be the one with least engineering cost.

It is possible to make the comparison between options using those portions of the collective dose that can be estimated with reasonable certainty. There is a hidden judgement in this, not usually acknowledged, that beyond those times when the uncertainties in collective dose rate are large, any detriment to health can be ignored. Without this judgement there is no logical reason to apply the uncertainty in the collective dose commitment to only part of the quantity. A simple analogy is to think of comparing the total lengths of two posts that are protruding from the ground. The difference in exposed lengths is no indication of the difference in total lengths.

In some cases it may be reasonable to assume that the collective dose rates from given radionuclide(s) in the environment are the same beyond some future time, even though they are uncertain. For example, if a longlived radionuclide is retained in a repository for 100 years in one option and 10 000 years in another, the component of collective dose from the globally distributed nuclide after 10 000 years may be taken as common to both cases and ignored in the comparison. In any case it seems reasonable that the option with the smaller-certain collective dose should be accorded some preference.

Small individual doses

There is considerable confusion in discussions of individual dose with ideas on 'de minimis', 'trivial', or 'negligible' doses.

If it is assumed that normal levels of radiation exposures increase the probability of deleterious effects on health then it follows that successive relatively small increments in radiation exposures will increase the probability of such effects linearly. In a population the increased expected number of deleterious effects will be proportional to the summation of all the small increments, i.e. to the collective dose. Hence, if we are considering populations and collective dose values of sufficient sizes that we expect at least one deleterious effect to some individual's health, then it can be argued that the number of deleterious effects that will be expected depends only on the size of the collective dose.

Individual members of the public may chose to ignore exposures to radiation that present a very low probability of harm to themselves. Such low exposures may appropriately be termed 'negligible' or 'trivial'. However, when a source of such exposures to many individuals is being considered it does not necessarily follow that the total impact of the source should be ignored. Were it to be so, rapid dispersion of wastes would always be the preferred way of disposal. Not only would this tend to increase collective doses "in someone else's backyard", but there could be legitimate concern that if low individual doses associated with any particular source were completely ignored, then the doses from many such sources could add to non-trivial individual doses. Therefore to argue that small individual dose contributions to the collective dose can be ignored (merely because they are low) is not sufficient. Nevertheless it can be argued that our concept of "equity" is such that we do allocate resources according to "health effect density" or in some way influenced by the probability of harm to individuals. Therefore, different distributions of individual doses perhaps should be taken into account in comparing options for waste disposal. It has to be done though with attention paid to whether there is the possibility of build up of doses from many sources and to concerns regarding geographical distribution of dose. These concerns are not readily included in a simple aggregative analysis (e.g. a cost-benefit analysis).

The same considerations counter the suggestion that assurance of very small (i.e. negligible) individual doses from a particular practice is a sufficient criterion for the radiological impact from that practice to be exempted from normal control. Very small individual doses and a small collective dose from present and possible future sources may be sufficient conditions to define a practice as exempt.

Wide-spread doses

Undoubtedly, longlived radioactive nuclides from uranium mining and milling wastes will cross international boundaries, just as do chemical contaminants. In an attempt to ensure equitable treatment of trans-boundary radioactive pollution the IAEA has suggested an "international value for α" to be used in cost-benefit analyses for optimizing. The intent is that this should be a minimum value for all countries and that if a country chooses to use a higher value for radiation doses within its boundary, then it would use no less a value for doses predicted to be incurred outside its boundary.

This may certainly be an equitable approach in a strictly source-related analysis. However, it is difficult to separate "individual-related" considerations from the analysis; that is, not to consider the point of view of the receiving country. A consequence of the cost-benefit approach using collective dose valued with this international α, is that the lightly-populated country 'downwind' of a polluting country is more likely to incur higher concentrations of the pollutant than would a heavily-populated country in a similar location. Greater spending on control measures would be warranted in the latter case. This is another instance where the logic of the strictly "source-related" analysis does not appear to be completely satisfactory.

Future Individual Doses

The ICRP's recommendation is that risks to future individuals should be limited on the same basis as those to individuals living now(2). Hence, calculation of doses and risks to members of a critical group should be carried out with no truncation of time. It is recognized however, that there are practical limitations to this and an IAEA Advisory Group tried to come to grips with this question for high level waste disposal. The arguments are relevant for uranium wastes. The group argues (3) as follows:

"Describing the environmental conditions for the human species in the future becomes more and more speculative when the periods considered are tens of thousands of years from now. For example, glacial episodes have occurred in a cyclical fashion, and the next ice age may appear within about 10,000 years from now. Significant changes in the biosphere will undoubtedly occur through these periods. The detailed environmental conditions and nutritional needs of individuals in the distant future may be different from those of today."

"Since neither the location nor the characteristics of far future human individuals can be predicted, dose and risk assessments may not be meaningful for periods longer than a few thousand years. This does not imply that the assessments for such longer time periods should not be made, but it indicates that other independent means may be needed to reinforce the conclusions of the dose and risk assessments as they enter the period of increasing uncertainty."

"One means may be to assure that the repository is not going to change appreciably the radiation environment of the future population. The dose upper bound and risk upper bound are less than annual doses from natural background. Therefore, if the doses and risks from a high-level waste repository to far-future individuals who are assumed to have our characteristics and our nutritional needs are less than the respective upper bounds, then there is the assurance that doses from the environment of any future individual are not going to be appreciably changed by a contribution from the repository."

"An additional means of assurance may be to compare far future concentrations or releases of radionuclides from the repository into the environment with concentrations or releases from natural sources such as the upper part of the earth's crust, the toxicity of different radionuclides being taken into account in the comparison."

Choosing the Disposal Option

The Nuclear Energy Agency of OECD recently completed an exercise (4) in applying the ALARA principle to uranium mine and mill tailings. The study concluded that simple cost-benefit analysis of collected dose commitment with a given disposal option (as a surrogate for the probability of health effects from radiation exposure) and the cost of protection are not very useful.

Figure 1 (from Reference 4) illustrates the limitations of this kind of analysis as an objective decision-aiding tool. The figure refers to a reference tailing site defined for an area in the Southwestern United States. The disposal options are a variety of covering layers of sand, silt, clay and gravel. The analyses in the study have looked at the incremental cost-effectiveness between the options. The study identified the options that would be the optimum for a given target spending level (in \$/man-Sv, the chosen value for α) and for different integrating times for collective doses.

In the figure "B" is the option with no cover, the base case. Option 1 has 1 m sand/silt: option 3, 1 m clay: option 4, 1 m sand/silt plus a gravel cap and a rip-rap slope cover: option 6, 1 m clay, 15 cm rip-rap plus a gravel cover: option 9 is a below-grade disposal (all others were above grade) with 3 m clay/shale cover.

It is quite clear that depending on the value chosen for α and the integrating time for collective dose, the preferred option can range from the base case (no cover, short integrating time, low α) to the major earth works (the low grade pit, long integrating time, large α).

The ICRP has recognized that the very formal cost-benefit analysis of the type advocated in its earlier publications presents this kind of difficulty and is not appropriate for many waste disposal decisions. In its most recent report on the topic (2) it recommends a way of making decisions as shown on Figure 2. The main point is the separation of radiation/health factors and appraisal of the effect of judgements (weighting) on the outcome of the analysis.

Conclusions

An analysis of the pros and cons of various disposal options made along the general lines illustrated in figure 2 can explicitly treat the difficult and subjective assessments that have to be made. Although decisions on fundamental principles need to be made a priori - for example, whether future doses are to be discounted - it is unnecessary in estimating collective doses to adopt definite "cut offs" for integrating times, distances or individual contributions. In comparisons, which is where such estimates will be used, realistic assessments of uncertainties will limit the significance of predicted differences.

For comparison of individual doses with annual limits there is no need to select, a priori, a cut off time. The more realistic approach is to use comparisons with other radiological inputs to supplement comparisons with a dose limit in the future when the characteristics of people's habitats are poorly defined.

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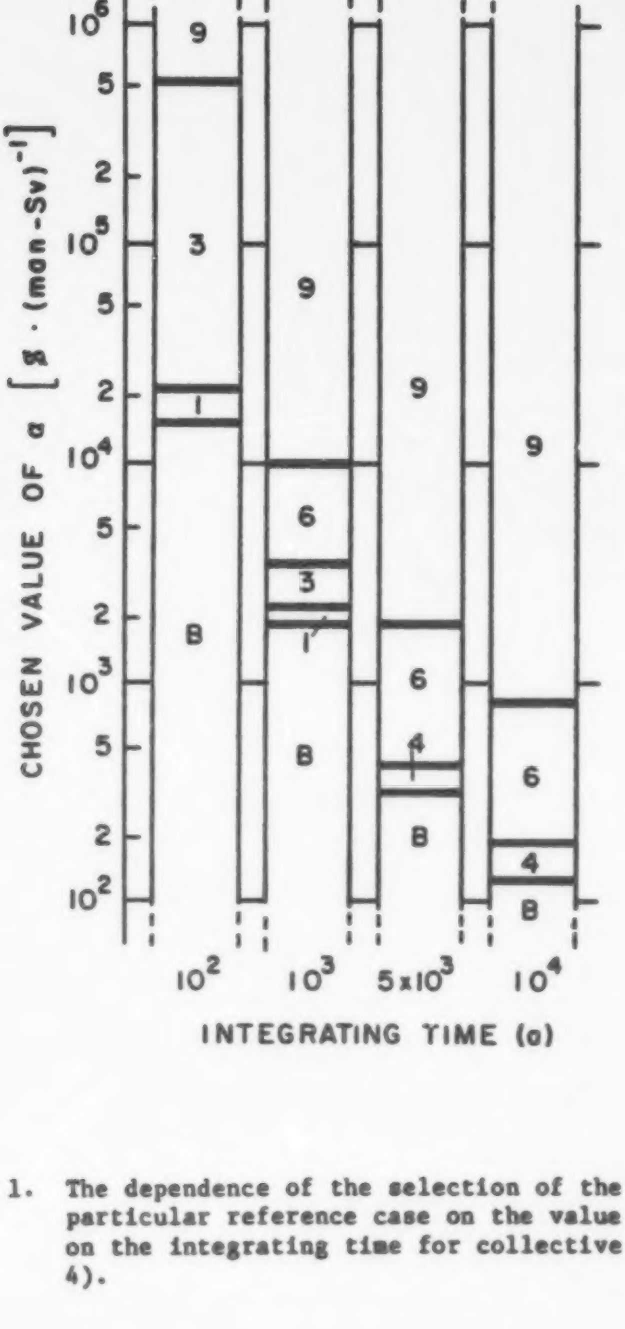


FIGURE 1. The dependence of the selection of the optimum option for a particular reference case on the value selected for α and on the integrating time for collective dose (from reference 4).

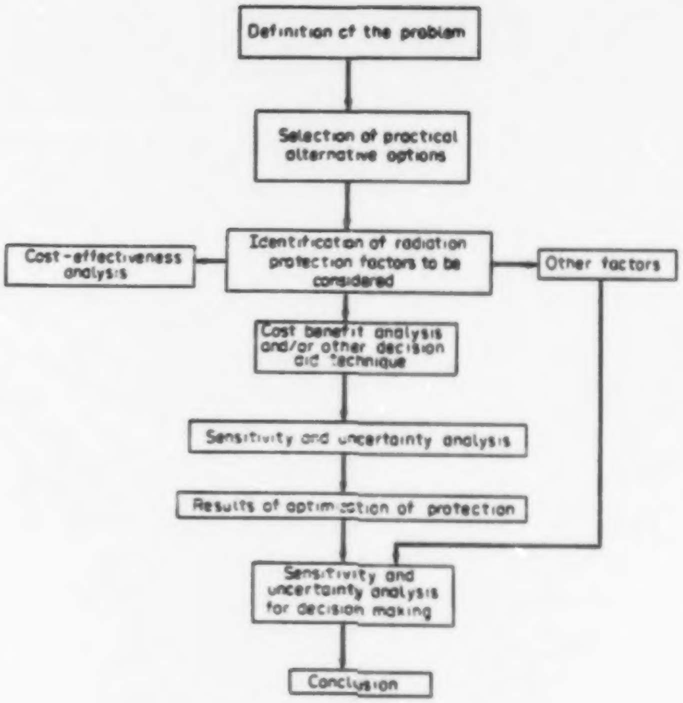

Definition of the problem
Selection of practical alternative options
Cost-effectiveness analysis
Identification of radiation protection factors to be considered
Other factors
Cost benefit analysis and/or other decision aid technique
Sensitivity and uncertainty analysis
Results of optimization of protection
Sensitivity and uncertainty analysis for decision making
Conclusion

FIGURE 2. Outline of radiation protection inputs to the process of deciding which disposal option to choose (from reference 2).

APPENDIX II

Appendix II Project Evaluation and Decision Processes

by Dr. James Dooley

II.1 Project Decisions, Techniques, and Decision Processes

This section contains a survey of some of the techniques that are available for evaluating and comparing projects when one is to be selected from a number of competing alternatives. No attempt will be made to describe the techniques in detail but references where details can be found will be given. The main purpose is to give an overview of the complex subject of decision making with particular attention to the problem of choosing a decommissioning option.

In the classical approach to decision-making three stages are used: identification, analysis, and choice. Identification includes the diagnosis and investigation of the problem. This stage may also include the creation of alternatives. In the analysis stage the alternatives are evaluated and compared on the basis of some specified criteria. The final stage is to choose from among the alternatives. Research has shown that there are many recycling steps so the stages are not just followed once in the order given. In the recycling steps the problem may become redefined or further alternatives created. Also the "stakeholders" (those who are responsible for the projects and those who are affected by them) may change in composition or attitude. The important point is that there is a process, not how the stages are subdivided, and that the decision evolves as a result of several modifications and passes through the stages. In this report the concentration will first be on techniques to analyze the options then on the decision process to incorporate them. The analysis stage typically consists of evaluation and comparison. Often these two aspects are combined as part of the same technique. For instance the simplex procedure of linear programming successively evaluates alternatives and finds better ones until the best is found within the structure of the technique (technically until no better one can be found).

Even though the power of analysis is great, it often happens, too often in the view of many analysts, that a thorough and careful analysis is ignored by the decision makers and the decision made without reference to the analysis. There are believed to be historical reasons why analysis generally has not found as much favour as it's apparent strength would indicate it should. Some reasons are suggested here primarily as a caution lest history be repeated and to suggest how analysis techniques fit into the broader process of decision making.

The three classical stages mentioned above, identification, analysis, and choice, have stood the test of time. They are applicable whether using only descriptive analysis or more complex techniques. Starting early in the twentieth century techniques began to be developed to represent simple decision situations. The economic order quantity technique of inventory theory is an example. During the second world war in the early 1940's the power of techniques to assist in making complex decisions was demonstrated. The discipline that created and applied the techniques became known as operational research in the United Kingdom and operations research in the USA. The early success and growing availability of computers to do the necessary extensive calculations stimulated considerable research into modelling of situations with specific structure purported to represent decision problems. The result was that the late 1940's to the early 1960's experienced an enormous growth in the number of techniques created. Along with this was a new wave of promise by the technocrats about how their techniques could "solve" decision problems. The techniques were indeed powerful and have proven useful but the tragedy was that they were oversold and did not fulfill their promise. The virtuosity of the technique creators gave them status that led those with problems to employ them to solve decision problems using their techniques. Unfortunately, the technique creators had limited experience about how decisions were made and were not particularly interested because they were convinced that they had a new way. They offered their techniques but often in inappropriate situations so the field fell into some disrepute although the usefulness of these techniques was not denied. Much of the early literature would start by saying: "if you have a problem defined by the following assumptions then here is a technique that will make the decision". This was easily translated into: "you have the following problem and here is a technique to solve it" otherwise they wouldn't have anything to sell. What was needed was one group to create techniques and another to investigate their role in decision-making. Fortunately, this is now happening and analytical techniques are filling their proper role in cases where the problem is investigated and then appropriate techniques selected and used but only as a part of the decision process. This project implicitly recognizes the need to investigate the problem first and then to investigate the techniques and systems that may be used to make the decommissioning decision.

The point of the foregoing commentary is to suggest an appropriate way to interpret the use of techniques. The collection of techniques should be looked upon as a catalogue of methods for analyzing problems of specified structure. Any technique can only represent selected aspects of the real decision problem but not all aspects. Thus, to see what aspects it is important to represent, the problem should be investigated first. It should be considered what simplifying assumptions can be made without distorting the representation in serious ways. Of course, it helps to have, in mind, the catalogue of techniques that are available just as a carpenter knows his tools and their capability when thinking about how he will tackle a job. Only then should decision techniques and analytical techniques be selected or developed. The next several sections discuss some of the evaluation techniques that are commonly used in project evaluation. This is followed by some concepts of decision processes that incorporate the evaluation techniques as part of the process.

II.2 Cost-benefit Analysis

Cost/benefit analysis is best thought of as a concept rather than a technique. The concept is simply that, for any alternative, the costs and benefits are assembled. Then if the benefit exceeds the cost, the project has a positive value and becomes a candidate for adoption. The benefits and costs can also be expressed as a ratio usually with the benefits in the numerator. If the benefit/cost ratio exceeds one then the project is favorable. Where there is uncertainty in the costs or benefits, concepts of risk analysis can be useful. Risk, in this work, is interpreted as risk to health, safety, and the environment as well as financial risk. Although primarily a concept, procedures have been developed for assembling the costs and benefits in particular contexts and some general procedures have been suggested. The problem is always to obtain appropriate costs and benefits. It will be argued later that some techniques, such as multi-criteria utility theory, can be used to provide the costs or benefits on a common scale.

Although the concept of cost-benefit analysis is simple, it is not easy to apply effectively. There are several considerations that have to be taken into account. These are:

(i) the determination of the costs and benefits to include,

(ii) the selection of measures that are suitable for expressing the costs and benefits,

(iii) the conversion of the different measures of cost and benefit to a common scale so that they can be compared and a net benefit or a benefit-cost ratio obtained. (In some cases there is no reasonable way to convert to a common scale and in such cases the costs or benefits may be considered separately), and

(iv) incorporation of a means of taking any important uncertainty into account.

It appears superficially that the costs and benefits to include should be obvious. Clearly, there is a project cost and benefits must be expected or the project would not have been considered at all except where the project is required by regulation such as in the decommissioning case. The cost is normally the simplest to determine. Typically, this includes the cost of land, materials and equipment, construction, and design. These costs are amortized over a specified number of years so the cost of borrowing has to be included. When the project is complete, there will be maintenance and operating costs. So far, the costs are the simple ones that we would expect to include. But what about costs such as the cost of a roadway that has to be built by the government or housing for those who may have to be moved from the decommissioning site: should this be included? Should the agricultural potential of the land used be included?

Turning to social costs; there are several things that might be included. As an example of social costs that might be included, suppose a landfill site is to be used. People may be displaced from their land, or may be subjected to risk due to transportation of the tailings, or from leachate. The topic of social cost has been explored under at least two main headings: social accounting, and social impact analysis.

The benefits from mining projects include profits, jobs created, contribution to balance of payments, and provision of a needed service. The benefit of proper decommissioning is reduced public risk and the value of this has to be determined. The problem is, of course, that the connection between the project and its benefits may be remote. A tailings disposal project does not appear to be beneficial except in terms of reduced risk but if considered in the context of the mine itself it becomes an integral part of the mine with its employment, profits, and the benefits derived from the use of the product. It is difficult to determine all of the benefits and certainly is difficult to quantify some of them.

The next step is to determine the measures of cost and benefit to use. Many costs and benefits can be expressed directly in monetary units. This applies to capital and operating costs, and, possibly, to the value of the jobs created. The natural units for measuring social costs are far from clear. The measurement of social disruption by, for example, a landfill is difficult to measure and the social benefits (by removing disbenefits) derived from less risk to health is also difficult to measure. The benefits of any jobs that might be created can be measured by contribution to GNP but there is also a social benefit if the quality of family life is improved as a result of the job. The decommissioning project is an example of a project that creates some risks but reduces others.

If all of the costs and benefits can be expressed clearly in monetary units then there is no problem in adding the bemefits and subtracting the costs to obtain a net benefit. Usually, it is not so simple because many of the costs and benefits cannot naturally be expressed in monetary units. A prime example is the problem of placing a value on human life. Work has been done on this problem for many years using such methods as present value of estimated lifetime earnings, or court settlements but these methods suggest a wide range in the value of human life. A housewife, for example, would not earn (in the sense of being paid) anything so would be worth nothing, on the basis of lifetime earnings, which is clearly not acceptable.

A common practice is to convert the various units for measuring costs and benefits to common monetary units using coefficients. The costs and benefits can then be added but the problem remains that the coefficients have to be determined using someone's values. (The coefficients represent trade-offs.). The linear multi-criteria utility technique discussed below is one way to convert to common units.

Finally, the uncertainty has to be considered. There may be uncertainty about the costs or the benefits. The uncertainty may be about where or when the risks will occur or the magnitude of the consequences. The probabilities of the different possible magnitudes of the consequence need to be estimated. As an example, one possible consequence resulting from leachate is cancer. A project may then be proposed that could reduce cancer cases by 0,1,2,...,n. The probability of each number has to be estimated. Typically, the expected number of cancer cases would be used (the average number in the statistical sense) but this ignores the range of possible cancer cases. A lot of public controversy occurs because proponents stress the expected (average) lives lost per year and this is typically a small number. In contrast the public is inclined to stress the number that could be lost in the worst case.

Many of these ideas have been explored in the pioneering work of Mishan [58] and gives in a popular version by Layard [59]. A very useful procedural approach is Dasgupta et al [60]. Wilson and Crouch [61] have attempted to include risk concepts but end up using expected values which limits the usefulness of their work but they do discuss the risk issues in some detail. Although several problems in the use of cost-benefit analysis have been discussed, the technique remains one of the most useful available. In fact all evaluations ultimately become a comparison of costs and benefits regardless of the techniques or analysis used before making the comparison. It is in this sense that cost benefit analysis can be thought of as a general concept rather than as a specific technique even though in some cases specific procedures are spelled out. An often cited value of working through some of the problems of using cost/benefit analysis discussed above is that those who involved in the analysis are forced to think carefully about the project and the criteria for it's evaluation even though the quantitative evaluation may not be as precise as desired.

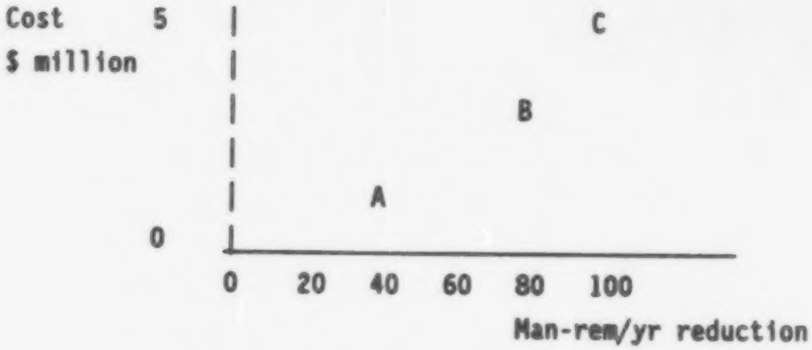
II.3 Cost-Effectiveness

Cost-effectiveness is a way of comparing the cost of an action with the benefit without having to convert to common units of measure. The technique generally is limited to comparing a single cost and a single benefit at one time although different pairs can be compared. Suppose, as an illustration that there are three decommissioning options under consideration, call them A, B, and C, with costs and benefits as shown below. The benefit is the reduction in radiation exposure compared with the "do nothing" option.

Disposal method	Cost, Millions of dollars	Exposure red. man-rem/year	Cost effectiveness
A	1	40	25,000
B	3	80	37,500
C	5	100	50,000

The cost effectiveness of A is 25,000 dollars per man-rem reduction, of B is 37,500, and of C is 50,000. We can see that the marginal cost per man-rem reduction is increasing and we have not had to place a dollar value on a man-rem. It is useful to plot the original data as shown in Figure 1

FIGURE 1 COST/EFFECTIVENESS CURVE



Any further alternatives that fall above the line are worse than these three because they are more costly per man-rem reduction. In comparison if a alternative could be found below the line it would be better than these three because it would cost less per man-rem reduction.

The example illustrates that cost effectiveness does not show which alternative is best, we know that C has the greatest benefit, but does show how much extra it costs per unit of improvement in benefit. In this case it costs twice as much per unit of benefit as A. It is a matter of judgement, or policy or values, whether the extra benefit is worth the cost. The value of cost/effectiveness is that it displays the trade-off inherent in the options very clearly. Cost/effectiveness can also be very useful for comparing the effectiveness of expenditures on competing activities in an allocation of resources problem.

II.4 Optimization Techniques - Mathematical Programming

The word optimal simply means the best. So when applied to decision-making, or more precisely to evaluation, the optimal alternative is the one with the best evaluation under the criterion. There may be some alternatives that are as good but none are better. The simplicity and idealism of the notion of optimal makes it an appealing concept because decision-makers want to choose the best and to be seen as choosing the best. Optimal, unfortunately, is often used to mean a good choice but not necessarily the best. Simon realized that the best in the strict meaning of the word is often difficult to find among the alternatives so coined the phrase "satisfying solution" to indicate a satisfactory choice but not necessarily the best.

In a more technical sense the term optimization is used as a property of a mathematical technique. Optimization techniques will find the mathematically best solution using only a single criterion and, of course, the solution is only "the best" within the assumptions and structure of the technique. Perhaps the best known optimization technique is linear programming. The criterion may be to minimize cost, or maximize profits, or minimize time or distance - but only one of these can be used in a particular application. The assumptions are that "everything is linear". Linear programming uses a set of "decision variables" to represent the choices. In tailings disposal, for instance, the variables could be the amounts of money spent on each of a number of different options or project components (similar to capital budgeting). The objective could be the reduction in man-rems of exposure . Linearity would be the assumption that, regardless of the amount spent on a particular project, there would be a constant rate of exposure reduction per unit of money spent on the project. Furthermore, the exposure reduction resulting from expenditures on any one project would be independent of how much, if any, were spent on other projects. This is clearly not realistic but does illustrate the idea. Any number of constraints could also be imposed but these also need to be linear. In this example the decision-maker might want to know how much to spend on each of a number of competing projects (the decision variables). The criterion would be to minimize radiation exposure and the constraints could be limits on the total budget or on individual projects and other constraints providing they can be expressed as linear equations. It might seem that the assumptions make the linear programming technique unrealistic and yet it is so powerful in its ability to pick the best and handle large numbers of variables and constraints that a lot of effort has been devoted to creating ways to express the important aspects of many types of problems as linear equations. This can be illustrated using simple notation. Let the decision variables be $x(1),\ldots,x(n)$, which we can take as the amounts to be spent on each of the n projects or parts of a decommissioning system. Let $c(i)$ be the amount of radiation exposure reduction per dollar spent on project i. A linear objective function can be expressed as $c(1)x(1)+\ldots+c(n)x(n)$ which gives the total radiation exposure reduction for an expenditure of $x(1)+\ldots+x(n)$. A typical constraint may be that the total expenditure on projects i and j combined must not exceed $b(1)$. This would be written $x(i)+x(j) < b(1)$.

There are several extensions to linear programming that allow non-linear aspects to be represented. These form a more general class of techniques known as mathematical programming. To mention a few, we have: integer programming, dynamic programming, goal programming and non-linear optimization. Non-linear optimization is the most general form of optimization technique. In non-linear optimization the linearity assumptions are relaxed for both the objective function and the constraints but it becomes much more difficult to deal with mathematically and computationally than linear programming and it is not always possible to find an optimal solution. Goal programming is a special formulation of linear programming in which there are several objective functions; one for each criterion. These are ranked by order of importance and the linear programming problems are solved using the objective functions successively starting with the most important. This is a very useful technique but cannot guarantee an optimal solution under all criteria. Dynamic programming allows non-linearity in the objective function but not interactions between variables. In dynamic programming the objective function can be written $f1(x(1))+\ldots+fn(x(n))$ where fi is the non-linear function giving the contribution to radiation reduction for an expenditure of $x(i)$ on the ith project.

An assumption in linear programming is that the variables are real and non-negative. In integer programming the variables are integer and non-negative. Mixed integer programming allows a mixture of real and integer variables. This extension allows a lot more features of many decision problems to be included but at the expense of computational cost.

Optimization techniques are important in decision-making because they give a good first solution to many decision problems. Their special contribution arises from their ability to reduce the complexity of decision problems, particularly when there are many variables and constraints.

There are many excellent references for optimization techniques. One of the most popular and not highly technical is Hillier and Lieberman [61]. Applications in the public sector are given in Gohagan [62], and McKenna [63].

II.5 Decision and Utility Theory

Decision theory starts with a model of simple structure. The alternatives in this branch of decision science are usually called actions. The suitability of each action depends on which of a number of possible future events occurs and there is uncertainty about which future event will occur. The suitability of each action for each future event is measured by a "loss function".

The technique operates in two stages. One in to evaluate each action (expected value is one criterion) and the second is to choose an action on the basis of the evaluation. Typically, but not always, the action that has the lowest average cost (expected in the statistical sense) or highest average gain is the action chosen. Another approach is to choose the action that will minimize the maximum cost. In this case the evaluation of each action consists of finding the maximum cost if that action is chosen and the worst future event occurs for that action. Then the action is chosen that minimizes the maximum cost. This is similar to a strategy that seeks to minimize the worst case, regardless of how unlikely it is to occur.

Utility theory extends the power of the decision theory technique. In some problems simple monetary value is inadequate to represent the gamble for the decision-maker. This is typical of risk situations in which people buy insurance knowing that, on average, they are expected to lose money but buy to protect against a possible large loss that would be ruinous.

This approach could be applied to the tailings disposal problem. The actions would be the decommissioning technologies or projects. The future events, with uncertainty, could be the amount of radiation released. The different projects may release the radioactive material through different pathways and so have different consequences such as cancers. The loss function could express the number of cancers over some period of time for each project and each amount of release. The minimum expected value approach would find the expected cancers for each project and then pick the project with the minimum expected value. It can be seen that considerable estimation is needed to employ this technique. First the amounts of possible release have to be estimated with their probability and then the cancers estimated for each release and project (hence pathway). There is a great deal more to this subject than has been suggested here. It was introduced as one of the profound ways of representing decision problems where uncertainty is present. A recent book by Bunn [64], gives a sound introduction and discusses applications to risk situations.

II.6 Multi-criteria Utility Techniques

So far most of the techniques introduced use a single criterion. It is quite clear, however, that in many decision situations it is necessary to try to satisfy several criteria to some degree. In most cases it is necessary to make a compromise between criteria to make a choice.

Consider the decommissioning problem. It would be desirable to find the cheapest way of disposing of the tailings and at the same time have the maximum security or minimum risk. This is like looking for the lowest priced car and the best car available. In both of these cases a compromise is necessary between cost and the quality of the product.

There are a multitude of techniques to resolve the dilemma of trying to satisfy several criteria simultaneously. One of the most popular is linear utility. In this technique the criteria are weighted in accordance with their relative importance. An alternative is considered under each criterion and a measure of its performance recorded. The alternative is evaluated by multiplying the performance measurement by the weight for each criterion separately and adding the products. This is very appealing because it produces a single number as an evaluation for each alternative. To apply the method we have to: find adequate measures of performance and evaluate the performance of each alternative under each criterion, decide whose weights to use and determine their weights. The linear utility technique also assumes that low performance under one criterion can be compensated for by an offsetting high performance under another criterion. Because of this trade-off feature, linear utility is one of a larger class of multi-criteria techniques known as compensatory techniques. In the linear technique the trade-offs are made between equal intervals of the weighted performance. For instance, suppose the performance of an alternative under one criterion is 5, with weight 0.3 and under another is 7 with weight 0.1. The linear utility of this alternative, ignoring other criteria, would be 2.2. A second alternative with a performance of 4 under the first and 10 under the second would also have a linear utility of 2.2. We have traded off one unit of performance under the first for three units under the second because of the weights chosen.

A second form of compensation is to trade off ratios in what is called the multiplicative utility technique. In this case, using the above example, we would have (.3x5)(.1x7)= 1.05 as the multiplicative utility for the first alternative. To make the utility of the two alternatives equal would require a performance of, say 4 under the first and k under the second criteria. To find k set (.3x4)(.1xk)=1.05 which gives k=8.75.

Another main class is non-compensatory in which trade-offs are not made but requirements are to be met under each criterion separately. There are several ways to apply the criteria which collectively create the class of non-compensatory techniques. Often the non-compensatory techniques are used to screen out alternatives that are not acceptable and then other procedures are used to evaluate the remaining acceptable ones.

A third class of multi-criteria techniques are lexicographic techniques in which criteria are applied successively in a prescribed order and only until a clear winner emerges. In sporting competitions it is common to declare the winner of a division as the team with the most points on the season's play. If only one team has the most points, then the choice is made and no other criteria are used. If the top two, or more, are tied then the second criteria is used which might be to declare the team that scored the most points as the top team. If this does not produce a clear winner the third criterion is applied and so on until a clear winner emerges.

Multi-criteria methods are recognized as of growing importance but have to be used with care. The validity of their use depends on being able to get adequate expressions of value, for instance the weights, from people deemed appropriate to supply the values. In simple repetitive situations, however, it is possible to develop useful linear utility techniques. Evaluating an individual's credit rating is an example.

The question is often raised about whether there exist a set of weights that are independent of any particular problem and can be used universally to represent society's values. The appeal of a set of universal weights is that they could be used in a particular problem without having to select people to express their values through weights and so avoid the problem of defending the objectivity of the exercise. Unfortunately this is unrealistic because a set of criteria weights can only have meaning when determined for the range of performances for the options in the particular problem. To see why, suppose people were asked to supply weights using one of the procedures for eliciting weights. Health and safety would be found to weigh much higher than anything else. Now suppose that, for a particular problem, the health risk is extremely low for all options but the environmental damage is very high for some of them. The high weight given for health could wash out the environmental factor and the evaluation of the options would be meaningless. If the weights were determined for the particular problem, the health criterion would weigh low as of little importance in selecting an option in this case.

Three excellent, but quite technical books have been written recently on the subject: Keeney and Raiffa [65], Goicoechea et al. [66], and Zeleny [67]. All three contain applications in the public sector.

II.7 Fuzzy Sets

Fuzzy sets have received a lot of attention recently as a way of making decisions when the problem is fairly unstructured. See, for example, Dubois and Prade [5]. In many decision situations it is difficult to obtain a numerical value for the probability of the consequences or a numerical measure for their cost or seriousness. It may, however be possible to get a verbal description such as a high, medium or low probability using a carefully constructed procedure. Likewise it may be easier to get a verbal description of the consequence such as serious, moderate or low. In fuzzy set theory these words would be mapped onto a scale of zero to one. If the probabilities are independent of the consequences then the evaluation of each option could be the minimum of the pair of mapped values for that alternative. The best alternative would be the alternative with the minimum evaluation since, in this case the consequence is unwanted so the least consequence is desired.

There is still a lot of controversy about whether this procedure adds anything that cannot be accommodated in decision theory or multi-criteria decision-making.

II.8 Global Judgement

Global judgement is an approach to decision-making in which an expert is given information about the options and makes a global judgement or choice from the options. An example from the medical field is where a doctor is given a number of test results for a patient and makes a judgement about the patient's condition. In contrast the test results could be entered into a technique of some sort that would predict the patient's condition. In the decommissioning problem that would be equivalent to presenting the decision-maker with information about the technology and the site for each option. He would then judge one to be best without explicitly expressing, or even knowing, how the information was used or combined to make the choice. Terms such as "intuition", "gut-feel", or "experience" are commonly used to mean the same as global judgement. This approach is used in a surprisingly large number of situations and often successfully. The confidence in the result is typically dependent on the track record of the decision maker. In the absence of an appropriate technique or technique to combine the information into an evaluation and choice, this may be the only method available. The problem is that this method is difficult to justify to a public body or a group of peers.

II.9 Decision Systems

In Sections II.2 to II.7, several classes of techniques were discussed in terms of their structure, strengths, and limitations. It was stressed that all of these techniques provide a form of evaluation of the alternatives but not the complete evaluation needed to make choices. They provide a useful input but that input must be combined with other factors to make a decision. A selection process that includes the evaluation and its combination with other factors, is a decision process or decision system. (see Section 3.1 of main text). This figure also acts as an example of the decision system based on the tailings decommissioning problem. This section will give a brief review of ideas on decision processes. First the elements will be described followed by a discussion of how the element are combined and how the process operates.

The first element is the "stakeholders". These are the individuals or groups who have a "stake" in the decision. They may be responsible for some aspect of the project or be affected positively or negatively by it. The stakeholders will take an interest in the decision but they may or may not have the opportunity to participate. This will depend on the setting in which the decision is made. For instance, in some cultures, there is limited opportunity for public participation in decisions about projects. The stakeholders may take different positions with respect to the project because of the way they are affected by it. A classic case is one in which a proponent wants a project for financial or other reasons and local people don't want it because of the risk it creates. A tailings disposal site is a typical example. This situation is so common that an acronym, NIMBY, has been coined for the phrase,"not in my backyard". The stakeholders provide part of the values that enter the decision. Other values arise from the culture.

The next element is the resources that are available to make the decision. These can be grouped conveniently into information resources and human resources. The information resources include traditional information and the technical and scientific facts that apply to the project. The techniques discussed previously are examples of information resources and so are recorded engineering and scientific knowledge. The human resources include stakeholder's knowledge and experience but, in addition, they supply judgement and understanding of the decision situation. The human resources also do the work of data gathering and evaluation.

A currently popular way to make the information resources available is to use a system called a decision support system. This is a type of system that allows the user to control the kinds of information retrieved and the analysis done on it. The name suggests the idea that the system supports, but does not make, the decision. A theoretical treatment of decision support systems is given in Bonczak et al. [68], and a good treatment of practical applications is given in Sprague and Carlson [69].

The third element is the stages that form the process. The classic stages are identification, analysis, and choice. Much research has been done to see if decision-makers actually use these stages (see, for example, Mintzberg et al, [70]). It has been found that they do but a lot of recycling takes place. One term for a pass through the stages is a "round". In a round a perception of the problem emerges, alternatives are generated, and positions taken by the stakeholders and, possibly, a detailed evaluation. This is a fluid process because, as the problem becomes re-defined for a round, the stakeholders may be affected in a different way so may shift their positions.

The fourth element is the management of the decision process. This concept visualizes a two level hierarchy. There is the operation of the stages, and there is a second level that directs the flow through the stages. An example of a second level decision is the decision about what evaluation technique to use. The upper level is sometimes referred to as the meta-decision process to indicate that it is concerned with "decisions about how to make decisions". The meta decision process has received some attention in limited ways in the literature but remains largely unexplored.

The fifth element is the established procedure and the decision-making authority. In many countries, an established procedure exists for reviewing projects in an environmental assessment procedure. This is an example of a structure for decision-making.

These five elements are brought together into a decision system. The elements can be summarized as given below:

Element	Primary Concern	
	Technical & Economic Evaluation	Cultural & Political
1. Stakeholders		X
2. Resources - information	X	
- human	X	X
3. Process Stages	X	
4. Management of process stages		X
5. Formal decision structure		X

Specifically, the evaluation techniques are resources (element 2) and using them is part of element 3, process stages. So the techniques provide a technical evaluation even though human values such as weights are used. The weights are used in a structured technique in a technical way. The judgmental part of the human input is used in the fifth element, the formal decision structure. Thus, evaluation techniques provide an input to the formal decision structure and may be used at the decision-makers discretion. There are also informal procedures, that are usually covert to the observer, so cannot be formalized.

This section has not attempted a full exposition of the large subject of decision techniques, processes, and systems. Instead it has attempted, by discussing the elements, to show the components, how they are brought together, and the role of evaluation techniques.

APPENDIX III

Appendix III Decision Techniques: Applications

III.1 Overview of Literature Search

Decision methods have been applied in a wide variety of diverse and varied fields. For the current, project a literature search of these applications was undertaken for a limited number of pre-selected topic areas. The details of this search are discussed in Appendix IV. Keywords were chosen in areas related to the uranium mine and mill tailings problem. These fields were searched explicitly and a detailed discussion of the various reports and articles are given in the following sections. Other areas or fields that have utilized evaluation processes, were also encountered in the literature. Since these were not extensively searched, these are only briefly mentioned in previous sections (Section 3 and Appendix II) and not detailed in the following sections. Only those that were specifically applied to a decision process are reviewed in the following section. Others, used to develop criteria values or papers descriptive of a method or tailings decommissioning alternatives were reviewed, entered into the annotated bibliography (Appendix IV) and discussed in the relevant sections of this report.

An overview of the papers searched and evaluated is given in Table IV-3 in Appendix IV. This table is organized alphabetically by author and summarizes the work done in the paper.

III.2 Uranium Mine and Mill Tailings

The literature on decision methods applied specifically to managing of uranium mine and milling wastes is not extensive. A number of general discussion articles and a few general applications of cost-effectiveness are available.

One of the most extensive applications of decision methods or systems arises from the Uranium Mill Tailings Remedial Action Project (UMTRAP)[6] study on remedial action. The decision system employed for this study involved the nonrecursive questionnaire polling of a panel of experts. The experts were asked, not only to rank and evaluate remedial alternatives, but also to establish the weights for the objectives. In the study two sites were evaluated (Salt Lake City, Utah and Shiprock, New Mexico) with 7 primary objectives:

1. Minimize cost
2. Final use to public
3. Optimize health and safety
4. Conserve petroleum
5. Conserve fossil fuel
6. Finish on time
7. Minimize deferred and external costs

The decision system (called a decision support system in the article) is based on the application of a Kepner and Tregoe [71] approach (K-T approach). In brief summary, the K-T analysis involves:

1. Identification of ultimate goals and description of current situation.

2. Set of objectives is generated and ranked as "musts" and "wants".

3. Alternative actions are generated and compared for their effectiveness in meeting objectives.

4. Sensitivity analysis.

Three approaches were employed to reduce the responses from the expert panel. The first approach used a cost-benefit utility factor (reciprocal sum of weighted extent of benefit for each alternative) multiplied by the cost of the alternative. This was defined as:

$$U(I) = \left(\sum_{j=2}^{J} a_{i,j} \right)^{-1} C_i$$

where $U(1)$ is the cost-benefit utility factor

$a_{i,j}$ is the weight, as a benefit, of alternative i contributes to objective j

C_i is the cost of alternative i

The second approach used was termed a relative cost factor (decimal fraction penalties for not meeting objectives) given by:

$$U(2) = \sum_{j=1}^{J} (w_j - a_{i,j})$$

where U(2) is the relative cost utility factor for i

w_j is the weight of objective i

The third approach involves the scoring of each alternative (1 to 10, with 10 assigned to the best alternative) and obtaining a weighted sum. This was defined as:

$$U(3) = \sum_{j=1}^{J} r_{i,j} w_j$$

where U(3) is the benefit utility factor

$r_{i,j}$ is the rating of alternative i with regard to attainment of objective j, in comparison with all other alternatives.

The authors of the report performed extensive statistical analysis of the initial input data obtained from their questionnaire. They were surprised at the wide range in weightings. It was felt that this variation would be greatly reduced using a recursive technique. The authors concluded that the ranking of options would not have significantly changed with a reduced variation in the weightings. Only the confidence intervals of the final cardinal ranking of the alternatives would have changed.

The extensive statistical analysis of the input weights revealed that the variation in objective weightings could not be described by a normal distribution. Responses for the effectiveness of the alternatives and their effectivness rankings were found to be normally distributed.

Application of their method lead to the conclusion that for the two sites considered, earth cover was preferred over asphalt cover, moving the tailings to a new engineered pit or a thermal stabilization process.

The paper provides a readily applicable method for inclusion in a decision support system.

In May of 1983, Chee et al [7] presented the results of a cost-effectiveness study for a uranium mill tailings site in Salt Lake City, Utah and a thorium processing facility in West Chicago, Illinois. Three alternatives were considered for each site: onsite stabilization (including cover), offsite disposal and a no action alternative.

The only factors considered in this study were cost and population dose reduction.

The results of the study showed that for the West Chicago site, the dose-reduction cost for on-site stabilization was about 20 times less than dose-reduction cost for offsite disposal. For the Salt Lake City site, this difference was approximately a factor of 10.

The authors also presented an interesting discussion on the population dose considerations during the remedial action. This was included in their cost-effectiveness calculation.

Their conclusions, in terms of preferred remedial action, did not change in their cost-effectivness calculations based on annual dose reduction or on a cumulative 200 year population dose.

In 1982, Osborne [8] and in 1983, Olivier, Osborne and Rafferty, [9] discussed the results of a OECD-NEA [10] study on the long-term management of uranium mill tailings. The study analyzed remedial actions using a cost-effectiveness approach. Three hypothetical reference sites (semi-arid, tropical and northern temperate) were considered.

The authors focused on the collective effective dose equivalent commitment as the basis for performing their optimization. No account was taken of temporal or spatial distribution of dose, nor of the distribution of individual doses. A upper limit of 10,000 years was considered. It was felt by the authors that "differences in radiological protection attained by different ways of managing the tailings would be masked by uncertainties in predicting the performance of engineered structures in the far future, and also by uncertainties in the dispersal and distribution of radionuclides". The authors also noted that different optimal solutions were possible depending on the time used to integrate the collective dose.

The authors criticised the direct application of a cost-benefit approach as being incapable of directly accounting for hazards from other contaminants. Other social and economic factors could also not be readily taken into account. Their conclusions [10] stated "that the cost-benefit approach to optimising radiation protection can only provide limited inputs to decisions on tailings management."

The results of their evaluation for a generic northern temperate tailings site, indicated that the construction of impermeable dams was the most cost-effective approach for the remedial actions considered for the criteria of cost and dose-reduction.

In 1985, Paschoa et al [11], presented the results of a very specific aspect of uranium tailings, namely the optimization (cost-effectiveness) of cover depths. The authors did not consider the effect of cover depth on dose from radon, but instead studied the problem from the point of view of either the maximum attainable radon flux reduction for a predetermined cost or a minimum cost for a predetermined radon flux.

Their procedure involved a direct application of radon flux attenuation modelling compared to normalized equations considering the differences in cost with various depths of cover.

The authors concluded that for a very limited application, the cost-effectiveness analysis approach could be used advantageously. They felt that one of the main strengths of applying this technique to a specific application avoided all of the pit falls of dose estimation and determining a dollar value for collective dose.

Van Dyke,[12] in 1983, produced a report for the U.S. Department of Energy, concerning the application of cost-benefit analysis to long-term isolation of uranium mill tailings. In this report, Van Dyke identifies the time frame that must be considered as one of the most fundamental and important criteria in deciding the cost-benefit ratio.

The author concludes that not only does the application of a classical cost-benefit analysis to uranium tailings involve the usual problems of a C-B analysis, but the need to consider an extremely long time horizon adds a fundamental ethical and moral judgement. Classical time discounting was not considered to be justified for long-term, intergenerational effects.

Van Dyke illustrated this discussion with a cost-benefit analysis applied to the setting of radon flux standards. From the moral and ethical point of view, the decision of regulated flux level should be set at either zero or at a level where the marginal costs of reducing radon are equated to the undiscounted benefits across all generations. The level was then established based on the authors' assumed value of a human life.

III.3 Low Level Radioactive Waste

In 1985, Short [13] reported a summary of the results of his masters thesis on a cost-benefit analysis to compare the alternatives of shallow land burial and greater confinement for the disposal of low level radioactive waste.

The paper details the development of the costs associated with the disposal alternatives, including various waste volume reduction options. The "risk" of each alternative was obtained by summing the doses to individuals (intruders were included) to a distance of 80 km. The dose was converted to a cost on the basis of $1,800 per person-rem. Other criteria were not considered.

Standard cost-benefit ratios were calculated and a sensitivity analysis was performed on the input parameters. Results were reported as the best alternative for different low level radioactive waste generators (eg. hospitals, power stations). Neither the results or ultimate use of the sensitivity analysis were discussed in this paper.

Hart [14] uses a very simple weighting matrix to evaluate various alternative sites for the disposal of radium wastes found in Denver, Colorado. Weights, totaling one hundred, were assigned to each of the 13 evaluation criteria (cost, public acceptance, lead time etc). Performance under each of these criteria were then evaluated and ranked. Sum totals of the weight multiplied by the performance under each criteria, resulted in final scores for each alternatives.

III.4 High Level Radioactive Waste

In 1983, Sioshansi[15] authored a paper concerning the use of an expert judgement system to evaluate alternate plug designs for deep geological high level radioactive waste disposal sites. The evaluation was based on polling individual experts in various relevant areas of knowledge (geotechnical, material behaviour, geochemistry etc) and deriving a "collective" result.

The use of a Delphi technique was rejected by the author on the basis that pressure is exerted within the group to arrive at a consensus. In most decision studies of this nature, the strengths and weaknesses inherent with different alternatives should be specified. This was not possible with the Delphi technique. With the current technique, responses were obtained independently.

The technique by Sioshansi involved the development of a comprehensive questionnaire, which required each evaluator to focus on specific aspects of the problem (ie. criteria). Ratings were performed on a four point scale (A to D) and evaluators where requested to provide a brief explanation of their evaluation. Though the questionnaire could be self administered, the current study used interviews to lead the evaluators through the questionnaire. For the 17 plug schemes suggested 15 questions were used. The total interviewing time was approximately eight hours per evaluator.

The results of the questionnaires were reduced by using a minimax principle. Due to the nature of the decision system employed in this study, not only were the "best" (ie acceptable to all fields of expertise) alternatives identified, but areas where improvements in design were possible and the rationale for low ratings could be identified.

In 1977, Otway and Edwards[16], applied a multiattribute rating technique to the evaluation and consideration of nuclear waste sites. The primary purpose of their work was to demonstrate multiattribute analysis and evaluate a number of alternative methods. As a result, criteria values were informally collected and were used for illustrative purposes only. On the other hand, the respondents requested to partake in the study were experts in the field.

The authors quickly rejected some of the more elegant techniques based on indifference gambles. The experts polled were concerned about the abstractness and lack of realism introduced in the hypothetical gambles.

The method utilized by the authors involved:

- eliciting ranges and values for the various criteria from the experts.
- obtaining normalized ratio weights (summed to 1) to describe the relative importance of each criteria.
- assigning values to the criteria for each alternative.
- calculating the additive utility for each alternative.

Mean values for the weights were used to calculate the utility value for each alternative.

The authors recommend that in cases where there are major differences in either the assigned weights or criteria values for the alternative, that the experts be contacted to further understand or even re-evaluate their initial decisions. The authors did not have the opportunity to take this step during their study.

The authors concluded that their method was successful in determining a defensible ranking of the hypothetical sites.

Vuori et al[17] studied the use of a cost-effectivness evaluation for high level radioactive waste management options in Finland. This approach was taken, as opposed to a cost-benefit evaluation, to avoid the necessity of assigning a monetary value to exposure levels.

A number of impact (exposure) criteria were used to compare alternatives. These were

- individual dose rate
- collective dose equivalent commitment
- integrated from closure
- during highest exposure
- as ratio to natural background
- average reduction of life expectancy.

Time discounting was not employed.

The authors concluded that in performing an analysis on the basis of individual dose rates, a probabilistic approach is desirable. Ranking of alternatives on the basis of collective dose gave the same ordering as for individual doses. This was not dependent upon the integration time used. Increasing the integration time decreased the differences in collective dose committment between options. The authors recommended the use of a limited time interval around the time of highest exposure as an appropriate option.

Comparisons to natural background and life expectancy calculations also gave the same ranking of alternatives, but were considered to give an extra benefit of placing the alternatives in perspective with other risks in society.

Kirkwood and Sarin[18] use a method of ranking multiattribute alternatives based on only partial information about the weighting. The method was found to be useful, not as a method of obtaining an optimal solution, but as a method of obtaining a set of alternatives requiring further investigation. The authors applied their technique to the choice of materials for borehole and shaft plugging in a high level waste repository. The developed method is relatively simple to apply and requires only a pair wise rating between the alternatives (ie. alternatives are compared in pairs). Actual weighting of the criteria was not required, only a ranking of the importance of the criteria was necessary. It does require criteria values for comparison. Using this approach, quartz, mullite and steatite were found to be the preferable set of materials for borehole and shaft plugging. Further preference between these materials was not possible by this method.

In 1982, Lathrop and Watson[19] used a decision system to differentiate between two high level waste repository sites. The method used by the authors was an extension of standard Multiattribute Utility Theory (MAUT) with an additive utility function.

The authors considered future effects as a separate criteria and did not attempt to discount or otherwise combine these effects with more current effects. In so doing, each decision maker was free to weight the future effects in what ever manner they considered reasonable.

Weighting values and utility functions were obtained by one hour interviews with each interested party. These values were then combined to obtain a group utility function by the use of equal weighting of calibrated utility functions. One of the drawbacks, as pointed out by the authors, is that, in their study, it was impossible to spend very much time (only 1 hr) with each decision maker.

In 1983, Salmon[20] used a decision system to choose between radioactive waste management options. The author realized the importance of considering numerous attributes in the decision process. The author developed a method whereby a limited number of alternatives were ranked on the basis of performance under each criteria. The stakeholders were then required to assign a weight to the various criteria. The stakeholders are then required to rank the options on the basis of their ranking under the criteria and their assigned importance to that criteria. In the real waste management case presented in the paper, the authors found that the same alternative was chosen by each group of stakeholders, though for different reasons. The authors note that the main benefit of their method is the structuring and clarification of the discussion. The authors did not comment or suggest methods of handling a situation where the stakeholders did not reach the same conclusions.

III.5 Hazardous Waste

In 1985, Horsak and Damico[21],[22], presented a paper concerning the use of fuzzy set analysis in the selection and evaluation of hazardous waste disposal sites. This study relies on the Yager (YAG77) procedure to evaluate the weightings of the various criteria.

Yager determines the relative importance of one criterion over another through the use of paired sets of criteria. By determining the eigenvector of the maximum eigenvalue the relative importance of the criteria are established. This eigenvector is then applied as an exponential weighting factor to determine the final weighted data. This enables the weighted criteria values for each site to be compared on an equivalent scale. In Horsak and Damico's study, the final ranking of the hypothetical sites is based on the lowest weighted value for each site (ie. best alternative has the highest minimum weighted criteria value).

Few details of the actual calculation procedure are supplied by the authors but a simple example allows the procedure to be readily derived. The questionnaire used for determining their paired comparisons of the 10 criteria used for their hypothetical disposal sites is given.

Shih and Ess[24] suggest the use of a multiattribute decision process in conjunction with a risk assessment for evaluating clean up alternatives at an uncontrolled chemical dump site. The decision process involves:

- the construction of a decision tree
- the completion of a detailed risk analysis on each branch of the tree as an initial screening process
- the conduct of a sensitivity analysis
- the completion of a multiattribute utility analysis on the remaining alternatives

The authors use a procedure based on the work of Rowe[25] to reject alternatives in the initial list of options by comparing objective risks (calculated risks for the alternative) with referent risks. This procedure, used with the risk assessment, compares risks across the entire spectrum (ie. involuntary catastrophic fatal risk through regulated voluntary, ordinary health risks). This procedure reduced the possible clean up alternatives to two from an initial set of 6 alternatives. These two were compared using a multiattribute utility analysis. Individual utility functions were generated and an additive multiattribute utility function was used to compare the remaining two options.

No indication is given by the authors as to the effort involved in completing the entire process. Since a detailed risk assessment is required before the multiattribute analysis is performed, it is expected that this is not a simple or inexpensive method to apply. The strength of this method lies in its ability to reduce an initial set of options through an examination of the risks. If all of the alternatives are found to be acceptable through this initial screening, the effort and problems will be the same as those found in using any single utility to multiattribute utility decision process.

The work of St. Clair and Sherman[26] presents a relatively simple and elegant cost-effectivness approach that allows the consideration of many non-specific (subjective) criteria.

The method used by the authors, consists of assigning weights to the criteria, rating each alternative for each criteria and eventually summing the weighted ratings. The cost effectiveness of the alternative is calculated by dividing the effectiveness rating by the sum of the costs. This is considered to be a "cost effectiveness score" for the alternative. The best alternative has the highest score.

The authors claim that even though this is not a mathematically rigorous approach, it is a useful in supporting decision about remedial actions. Its ease of use and its relative simplicity allow it to be readily understood by non-technical persons. In addition the method allows a quick sensitivity analysis to confirm the final rankings. The authors recommend a Delphi approach to eliminate outliers in the weighting or rating development phase of the analysis.

In 1986, Jennings and Suresh[27], presented a comprehensive paper on the application of fuzzy set analysis to hazardous waste management options.

The work relies heavily on a computer algorithm to solve the fuzzy set matrix and obtain a ranking of alternatives on the basis of risk. The authors feel that the ability to use these algorithms interactively on a computer system is a very strong benefit of this approach. All interested parties, involved in the decision process, could then use this method to rapidly evaluate their options. The authors are quick to point out that their approach is only useful in the early stages of a decision process, at a point where the decision makers are trying to form their preferences and potential tradeoffs.

Shecter[28], in 1985 uses a cost-effectiveness approach to study various groundwater protection and management policies near the Price Landfill site in New Jersey. The study focused heavily on the development of the risk estimates from ingestion of the contaminated groundwater. The author uses the range of risk estimates to develop a range of cost-effectiveness for each option. It was noted that the great variation in results came from the great variability in the risk estimates. No consideration was given to intergenerational effects.

III.6 Other Mine Wastes

No relevant literature was found concerning the decommissioning of mine wastes.

III.7 Siting - Nuclear Power Plants

The literature abounds with the application of multiattribute utility theory (MAUT) techniques for the siting of nuclear power plants. The literature is dominated by the work of Keeney[29-37] who pioneered much of the development of MAUT. A description of the method is not warranted in this discussion. Only those aspects in the various studies that are relevant or of interest to the current study will be highlighted.

Others, such as Church and Thomas[40], have developed methods for baseline screening of candidate areas. Though these are formal decision processes, the methodologies are too specific to the screening problem to be useful for optimising tailings management options. As a result, these papers are not reviewed in this report.

Solomon and Haynes[41] present a detailed critique of multicriteria decision methods applied to nuclear power plant siting. Their work draws upon an extensive review of 48 real site selection studies and an overview of the methods used in these studies provided by Brookhaven National Laboratory [42]. 13 of these studies used a multicriteria decision process. Of these, 8 appeared to violate the requirement of attribute independence and 10 of the studies appeared to violate the requirements for scaled attribute values and weights. The authors of the Brookhaven Report[42], felt that in some of these studies the final ranking would not have been altered if the problems were corrected.

The authors give a detailed discussion of the rationale behind the use of multiattribute systems. They contend that one of the principal uses of all decision systems is the ability to provide the decision makers with information at different stages of the project. They conclude that there is no single multidimensional algorithm or model suitable to power plant siting. The nature of the problem and even the characteristics of the sites will dictate the optimization procedure. The authors also conclude that all of these methods are decision aids, not replacements for the decision process.

One of the more critical steps in performing a MAUT analysis, is the determination of attribute weighting. In 1980, Hobbs[43] considered a number of weighting methods and evaluated them in the context of nuclear power plant site selection in the western Maryland area.

Of specific interest, is the studies use of weights derived from trade-offs versus weights derived from a ranking scale (not a ratio scale!) of 0 to 10. These two methods were used to evaluate the results of a regional screening study for candidate sites.

The authors found that there were significant changes in the chosen areas between the two weighting techniques studied. Overlap of the chosen areas was only 52%. They concluded that in order for a weighting technique to be valid, weights must be on a ratio scale.

In an interesting study by Ford, Keeney and Kirkwood[44], a number of evaluation or decision systems were considered for their applicability to the nuclear power plant siting problem. In effect, the authors perform a multi criteria evaluation of the various evaluation methods. Both regional screening to obtain candidate areas and specific site selection methods were considered. Only the methods for site selection are sufficiently specific to be used for tailings management decisions.

The methods considered were:

- Favourability selection: a site is chosen on the basis of its merits. No alternative site is considered.

- Qualitative comparison: qualitative comparison between alternative sites.

- Cost-effectiveness analysis: a site is chosen on the basis of engineering cost. Other impacts are considered qualitatively.

- Site Rating: a site is chosen on the basis of a rating scheme applied to all sites. No weighting factors are used.

- Comparison screening: MAUT

The methods were compared on the basis of the following three major criteria:

- quality of analysis (defensible etc)

- public perception

- practicality

These criteria were further expanded into 12 distinct attributes. Three individuals involved with the nuclear power plant siting were used as the decision makers in evaluating the methods.

The results revealed that comparison screening (MAUT) was superior to the other methods for site selection. In fact favourability screening and comparison screening were found to be the only non-dominated methods considered. All of the methods, as applied in the reference studies, were considered to be poor in their ability to handle public input, multiple concerns, uncertainties and long term impacts.

In 1982, Abdul-Fattah and Abulfaraj[45], used a fuzzy set method to choose between two potential nuclear power plant sites in Saudi Arabia.

It was recommended by the authors that fuzzy set be applied in a similar fashion to a normal MAU process. The application of fuzzy set theory, in this fashion, eliminates the requirement that the decision maker must assign specific numerical values and uncertainties. For the purposes of their study, the authors used a simpler ranking system. Rating and ranking were done on the basis of verbal description, rather than specific numbers. The authors used the MAFDA computer program, developed by Watson et al.[46], to calculate their final preference.

This method was successful in differentiating between the two sites.

III.8 Other Waste Handling

Multiattribute utility theory was used by Collins and Glysson[47] to decide between two different municipal waste disposal options. There were no deviations from the standard MAUT methods used in the literature.

The authors used a Delphi technique (experts are assembled around a table and discussion on a specific topic is continued until a conscensus is reached) to obtain the utility and weighting functions. Two evaluators, familiar with the field of solid waste disposal were used as the decision makers.

The authors point out that one of the strengths of this decision process rests on the ability to focus future effort towards areas that are identified as critical or significant and not waste effort on studying the details of criteria that do not effect the final decision.

In a study on sewage sludge disposal options for the Boston area, Perlack and Willes[48], utilized a linear programming model to reduce the options to a noninferior set and to focus important information required by the decision maker. This method was employed since there were a number of interdependent possible actions and combinations of actions (eg ocean discharge, incineration, landfill). Each of these actions had a number of constraints such as volume and cost. The authors decided upon the use of non-linear programming as the preferred method of generating the possible combinations of disposal options.

This study was undertaken as a followup study to work performed by Ecol Sciences[72]. This latter study attempted to judge 101 impacts by assigning ratings to beneficial and adverse effects. The alternatives were ranked on the basis of the sum of their impacts. This study did not address the relative importance of the various impacts.

The method used in the Perlack and Willes paper is based on cluster analysis[73]. This method partitions the set of determined alternatives into groups that are relatively homogeneous and mutually exclusive. Specifically, non-linear multiple object programming was used to generate a set of all feasible and possible solutions. For this study, 20 distinct solutions were generated. Cluster analysis (a method of grouping similar options) was then used to reduce the 20 solutions to 7 distinct groupings. Non of the seven options was clearly the best.

The authors suggest that the reduced set of options and the related data is invaluable to decision makers. Information overloading is minimized and the matrix of information can, if desired, be used as the basis for a multi attribute utility study.

The method used by the authors to handle uncertainty is an interesting feature of the study. Many studies deal with uncertainty as an input to a sensitivity analysis. The Boston study considered uncertainty to be a separate criteria. The uncertainty associated with each of the seven alternatives was presented as a evaluation criteria in their final matrix.

In 1981, Sobral et al.[49] applied a multi criteria procedure, based on fuzzy set analysis, to the evaluation of solid waste disposal alternatives in the Regional Municipality of Waterloo, Ontario, Canada.

Cost-benefit analysis was rejected by the study team due to its inability to handle environmental and social impacts that could not be measured in monetary units.

During this study, each interest group was requested to evaluate the alternatives and assign weights to the criteria. The Delphi technique was used within each group to arrive a consensus.

Various methods of aggregating these matrices were considered (mean, weighted mean, maximum, etc) to produce one solution matrix of criteria and alternatives. The mean and a modified pessimistic (average of the mean and pessimistic matrices) approach were used for the Waterloo study.

In 1979, Chen et al.[74], used a participatory decision system to resolve disputes in the installation of a solid waste shredding facility. Their system, called Value Oriented Social Decision Analysis (VOSDA), allows differences in decision trees, differences in probabilities assigned to branches in the trees and differences in preference and utility functions. One of the principal aims of VOSDA is the identification of conflicts between different interested parties. It is used as a tool to identify and resolve these differences. The authors state that "the purpose of VOSDA is to enhance the quality of the process rather than obtain an output".

A multi-criteria evaluation (MCE) technique was used by Maimone[50] to compare solid waste treatment and disposal options in the Netherlands. The method utilizes the concept of alternative dominance (ie. pair wise comparison) to generate a dominance matrix. Both ordinal and cardinal rankings are used in the evaluation. This is followed by the application of criteria weights to determine the overall dominance matrix. Appraisal scores are then additively generated for each alternative. The matrix concept allows the decision maker to consider each alternative on the basis of the appraisal score, but also for the strengths and weaknesses under each criteria.

APPENDIX IV

APPENDIX IV

IV.1 Literature Search

The evaluation methods, applications and databases searched are shown in Table IV-1. This table indicates the number of references found in each database for various combinations of the keywords. For searches where the number of citations was on the order of 100 or less, abstracts were immediately obtained. For those searches where the number of citations was on the order of 200 to 300 (for example, 4+a+b+g and 6+a+b+g), a title listing was obtained. The title listing was used as a screening tool to reduce the number of citations to a workable number. Abstracts were ordered for the reduced list.

The abstracts were then read and a set of useful papers and reports identified. These were obtained.

Upon receipt of the papers and reports, the articles were reviewed and entered into the annotated bibliography database. Important and relevant citations, within the reviewed articles and reports were also obtained and reviewed. Relevant studies are cited throughout the report.

Abbreviations used in the annotated bibliography, are shown in Table IV-2.

A summary of the annotated bibliography is given in Table IV-3.

Table VI-1 - Computerized Database Search - Number of Citations

Method Keyword	Application Keyword
1 - Multi(w)attribute or Multiattribute	a - waste or wastes
2 - Multi(w)objective or Multiobjective	b - tailing(?)
3 - Multi(w)criteria or Multicriteria	c - uranium
4 - Cost(w)effectiv(?)	d - decommission(?)
5 - Cost(w)benefit	e - siting
6 - Decision(w)making	f - nuclear
7 - Decision(w)analysis	g - landfill(?)
8 - Decision(w)theory	h - any of the above
	o - optimiz(?)

Preliminary Search

		Method								Applications	Method and Applications							
Database	Date	1	2	3	4	5	6	7	8	h	1 and h	2 and h	3 and h	4 and h	5 and h	6 and h	7 and h	8 and h
NTIS	64-86	228	124	44	12156	2438	13982	425	3013	203542	24	22	0	1246	703	1105	69	78
Compendex	70-86	189	357	184	5354	777	2927	310	2953	86397	13	20	5	461	110	176	39	107
Inspec	77-86	250	502	290	887	639	3874	337	3385	111373	21	13	2	350	120	157	43	68
Metadex	66-86	0	1	1	716	26	63	3	2	23155	0	0	0	39	3	3	0	0
EI Engineering Meetings	79-86	51	125	50	2390	444	1483	221	850	32394	7	4	4	234	72	78	20	24
Enviroline	70-86	18	75	6	828	442	1708	35	12	23539	7	5	1	238	97	239	12	0
Pollution Abs.	70-86	5	38	4	642	930	316	23	4	28120	1	7	1	285	317	88	18	0
ABI/Inform (Bus. Man.)	71-86	194	125	81	4130	957	11013	537	788	4775	5	3	1	88	15	115	15	3
Chem. Abs.	69-86	5	20	5	137	27	66	15	14	680410	5	4	1	36	12	12	8	2

Second Level Computer Search

		Method and Application and Optimiz(?)					Method and Specific Application		
Database	Date	4+h+o	5+h+o	6+h+o	7+h+o	8+h+o	4+a+ b+g	5+a+ b+g	6+a+ b+g
NTIS	64-86	65	41	57	4	11	791	381	425
Compendex	70-86	22	9	9	1	9	303	44	64
Inspec	77-86	22	15	9	3	3	152	60	38
Metadex	66-86	1	0	1	0	0	29	1	1
EI Engineering Meetings	79-86	7	4	3	0	5	233	29	32
Enviroline	70-86	7	7	4	0	0	311	55	150
Pollution Abs.	70-86	5	11	3	0	0	180	247	55
ABI/Inform (Bus. Man.)	71-86	2	0	2	0	0	60	7	58
Chem. Abs.	69-86	5	0	1	0	0	35	4	5

	METHOD				APPLICATION								USAGE			
Ref.Code	Cost-benefit	Cost-effect.	Multi-attrib.	other	Tailings	LLRW	HLRW	Haz.Waste	MineWaste	Siting	OtherWaste	Other	Descrip.	Applic.	Criteria	Other
AB082			T	fuzzy set						T		nuc. plants	T	T		
ASC86					T	T										
ASH76				risk benefit								energy				
BAI85						T								T	T	
BAR75	T											power generation	T			
BAR80	T							T					T			
BAR86					T				T				T			
BAR86a					T				T				T			
BEM80	T											nuc. safety systems	T			
BOH84				comput. D.S.S.									T			
BUE76			T									elect. generation	T	T		
CHE79			T	decision sys.							T	municipal waste	T	T		
CHE83		T		ALARA								nuclear plant operations		T		
CHE84		T			T									T	T	
CHO85			T									Nuclear Power Plants	T	T		
CHU81			T									Site Screening	T	T		
CLA79	T											rad. protection	T			
COH75			T										T			
COH78			T				T									
CON81				T									T			
CON82		T					T						T			
CON83															T	discounting
COL80			T								T		T	T		
COL82					T								T		T	
DIC83						T									T	costs
DOV83									T			coal mine waste	T			
DOW79			T										T			
EDW75			T	SMART								(see comment)	T	T		
EDW77			T	SMART								(see comment)	T	T		
EIC76	T											nuclear plant systems	T	T	T	
F[illegible]82	T	T	T	risk ass.									T			
[illegible]85				risk ass.								waste streams	T	T		
FIS67			T	utilities									T			
FLE82												rad. discharges			T	time discount
FOR79			T							T		evaluation of methods				
FOR84		T										leachate control		T		
GOT81			T									energy alternatives	T			
HAI74			T										T			
HAR86			T	matrix weight.		T							T	T		
HIL83							T						T			
HIP82			T	fuzzy set												
HOB80			T	screening						T			T			
HOB80a			T	weighting csth.						T		nuclear plant	T	T		
HOB85			T					T					T	T		
HOB85a			T					T					T	T		

	METHOD				APPLICATION								USAGE			
Ref.Code	Cost-benefit	Cost-effect.	Multi-attrib.	other	Tailings	LLW	HLW	Haz.Waste	MineWaste	Siting	OtherWaste	Other	Prescrip.	Applic.	Criteria	Other
HOW81				cost/risk anal.									T			
JEN86				fuzzy set				T					T	T		
KAT83				risk ass.									T			
KEE73			T	MAUT								Mexico - Airport		T		
KEE74			T	MAUT								Mexico Airport Study	T			
KEE75a			T							T		nuclear plants	T			
KEE75b			T							T		post. management	T	T		
KEE75c			T									energy systems	T	T		
KEE77a			T									energy systems	T	T		
KEE77c			T	Decision analy.						T		nuclear plants				
KEE79			T	MAUT								(see comment)				
KEE81a			T							T			T			
KEE81b			T	quant. attrib.						T		nuc. plant siting	T			
KEE83															T	discounting
KEL85												nuclide emissions				discussion
KEN86																chem. hazards
KIR82			T	decision tree						T		nuc. plants		T		
KIR85				ranking			T						T	T		
KOF80				deci. analysis								nuclear power				
LAN80					T										T	gen. decom.
LAT82			T	MAUT			T							T		
LAW86					T								T			
LIP82								T							T	costs
LIP86								T							T	occupational
LOB84		T										nuclear power plants		T		
LOC81	T	T										rad. protection	T			
LOW79			T	Electra								entire fuel cycle	T	T		
LOW79a	T	T	T	Electra.								entire fuel cycle	T	T		
MAA82		T											T		T	
MAC80						T										
MAI85			T	decision sys.							T	disposal alternatives	T	T		
MCA80				comparison												
MCK79				decision anal.			T							T		
MEY69																
MUR83			T	utility fun.								energy management	T	T		
MAI76			T							T		four applications	T	T		
MAI80		T														
MEA84																
MEW77			T									auto selection	T	T		
OLI84		T			T								T	T		
OSB82		T			T									T		
OSB84						T	T						T			
OTW77			T				T			T			T	T		
OTW77a				risk ass.								nuclear power	T			
OU081			T	outranking								U-cycle		T		

	METHOD				APPLICATION								USAGE			
Ref.Code	Cost-benefit	Cost-effect.	Multi-attrib.	other	Tailings	LLW	HLW	Haz.Waste	MineWaste	Siting	OtherWaste	Other	Descrip.	Applic.	Criteria	Other
PAS85		T			T							tailings cover		T		
PER85			T								T		T	T		
POC79	T															discussion
RIC85																
ROG82					T								T		T	
ROW79																
ROY71			T										T			
ROY83			T	oot ranking						T		Nuclear Power Plant	T	T		
SAA80																
SAL83			T	doc. system			T						T			
SHE85		T									T	landfill		T		
SHI81				multi obj.			T					in plant		T		
SHI82			T					T						T		
SMO85	T					T									T	cost
SIO83				sub. evaluation			T					Plug system for openings				
SIS83				Electra								elect. gen. methods	T	T		
SLO80				fault tree,risk			T						T			
SOO81			T								T			T		
SOL84			T							T		nuclear power plants	T	T		
SPO82												waste surround			T	
STA77			T										T			
STC82	T	T	T	comparison				T					T			
STI69			T	utility								grant allocation	T			
STI81			T	weighting tech.									T			
SZI82			T						T					T		
THO82	T	T		optimization								none	T			
THO83			T	Decision analy.	T								T	T		
VAN83	T	T			T										T	time value
VIN81			T									general	T	T		
VOO84		T				T	T							T		
WAT82			T										T			
WEB81	T	T		ALARA								rad. protection	T		T	
WEB83	T		T										T		T	
WEB84	T		T									nuclear waste (all)	T	T		
WER84								T							T	costs
WOO78			T	risk ass.									T			
ZAO73			T	fuzzy set									T			
ZHO79			T	fuzzy set									T			

Annotated Bibliography

ABD82

Author:	Abdul-Rahman, F.A., Waleed, H.A.
Title:	Siting of Nuclear Power Plants in Saudia Arabia using Fuzzy Decision Analysis
Journal:	Nuclear Technology

Volume: 58 Date: Sep., 1982 Page: 404

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other fuzzy set
Description T	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application nuc. plants	

Additional Comment: computer assisted

Annotated Bibliography

ASC86

Author: ASCE Task Comm. on LLRW Mgmt.

Title: Management of Inactive Uranium Mill Tailings

Journal: ASCE Journal of Environmental Engineering

Volume: 112 Date: Jun., 1986 Page: 490

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T	T	
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: good description of U.S. problem
volumes, actions, costs

Annotated Bibliography

ASH76

Author: Ashley, H., Rudman, R., Whipple, C.

Title: Energy and the Environment:
A Risk Benefit Approach

Journal:

Volume: **Date:** 1976 **Page:**

Publication Type: BO **Source:** LC-UOT

Additional Reference Comment: NUTS

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other risk benefit
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application energy	

Additional Comment:

Annotated Bibliography

BAI85

Author: Baird, R.D., V.C. Rogers

Title: Generalization Economic Model for Eval. Disposal Costs at a Low Level Waste Disposal Facility

Journal: Waste Management '85

Volume: 3 Date: 1985 Page: 461

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
	T	T	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
	T	
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: theor. discounting costs

Annotated Bibliography

BAR75

Author: Barranger, S.M.

Title: Decision Analysis of Energy Alternatives: A Comprehensive Framework for Decision-Making

Journal: Energy & Environment Cost-Benefit Analysis

Volume: Date: 1975 Page: 549

Publication Type: CO Source: AB

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T			
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application power generation	

Additional Comment: very general

Annotated Bibliography

BAR86a

Author: Barth, Richard C.

Title: Reclamation Technology for Tailing Impoundments
Part 2: Revegetation

Journal: Mineral and Energy Resources

Volume: Date: 1986 Page: 1

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
	T	
Other Waste	Other Application	

Additional Comment: description of revegetation process

Annotated Bibliography

BEN80

Author: Beninson, D., Gonzalez, A.J.

Title: Current Nuclear Power Plant Safety Issues: Optimization of Nuclear Safety Systems

Journal: International Atomic Energy Agency

Volume: 2 Date: 1981 Page: 449

Publication Type: CQ Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T			

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application nuc. safety systems	

Additional Comment: optimizing systems for low prob. events

Annotated Bibliography

BON84

Author: Bonczek, R., Holsapple, Whinston

Title: Developments in Decision Support Systems

Journal:

Volume: Date: 1984 Page: 141

Publication Type: BO Source: CH

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other comput. D.S.S.
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: computerized decision support system
review
NUTS

Annotated Bibliography

BUE76

Author: Buehring, W., Foell, W.,Keeney, R.

Title: Energy/Environment Management: Application of Decision Analysis

Journal:

Volume: Date: 1976 Page: 1

Publication Type: RE Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application elect. generation	

Additional Comment: complexity of problem
good description

Annotated Bibliography

CHE79

Author: Chen, Kan

Title: Value Oriented Social Decision Analysis: Enhancing Mutual Understanding to Resolve Public Policy Is.

Journal: IEEE Transactions on Systems, Man, and Cybernetics

Volume: SMC-9 **Date:** 1979 **Page:** 567

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	decision sys.

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting

Other Waste	Other Application
T	municipal waste

Additional Comment: dec. system literature participant system; simple form of MA

Annotated Bibliography

CHE83

Author: Chester, R.O. and L.D. Voorhees

Title: Cost-Effect. Considerations in Reducing Occup. Radiaton Exposure in Nuclear Power Plants

Journal: Nuclear Safety

Volume: 24/6 **Date:** 1983 **Page:** 821

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		ALARA
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application nuclear plant operations	

Additional Comment: occ. dose reduction options

Annotated Bibliography

CHE84

Author: Chee, P.C.

Title: Costs and Benefits of alternatives for Mill Tailings Management: A Perspective

Journal: Radioactive Waste Management

Volume: 4 **Date:** 1984 **Page:** 395

Publication Type: CO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		

Description	Application	Criteria Value	Other
	T	T	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: some costs of disposal

Annotated Bibliography

CH085

Author: Cho, N.Z.

Title: A Decision-Theoretic Methodology for Reliability and Risk Allocation in Nuclear Power Plants

Journal:

Volume: **Date:** 1981 **Page:** 14-1

Publication Type: CO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other
Description T	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application Nuclear Power Plants	

Additional Comment:

Annotated Bibliography

CHU81

Author: Church, R.L., Bell, T.L.

Title: A Comparison of Two Baseline Screening Approaches to Regional Energy Facility Siting

Journal: GeoJournal Supplementary Issue 3

Volume: **Date:** 1981 **Page:** 17

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application Site Screening	

Additional Comment: baseline screening methods, general proceedures, nuts

Annotated Bibliography

CLA79

Author: Clark, M.J., Fleishman, A.B.

Title: The Implications Of Cost Benefit Analysis For Optimization

Journal: Radiation Protection Optimization: Present Exp. and Methods

Volume: **Date:** Oct. 3-5, 1979 **Page:** 85

Publication Type: CO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T			

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings

Low Level Rad. Waste

High Level Rad. Waste

Hazardous Waste

Other Mine Waste

Siting

Other Waste

Other Application
rad. protection

Additional Comment: NRPB, increasing alpha with increasing dose, example of effect

Annotated Bibliography

COH75

Author: Cohon, Jared L.

Title: A Review and Evaluation of Multiobjective Programming Techniques

Journal: Water Resources Research

Volume: II/2 **Date:** 1979 **Page:** 208

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: comparison of methods

Annotated Bibliography

COH78

Author: Cohen, Jerry J.

Title: Review of Issues Relevant to Acceptable Risk Criteria for Nuclear-Waste Management

Journal: Waste Management & Fuel Cycle '78

Volume: **Date:** 1978 **Page:** 175

Publication Type: CO **Source:** PC

Additional Reference Comment: abstract only

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: very general discussion paper

Annotated Bibliography

COH83

Author: Cohen, Bernard L.

Title: Discounting in Assessment of Future Radiation Effects

Journal: Health Physics

Volume: 45 **Date:** Sep., 1983 **Page:** 687

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value T	Other discounting

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: discounting: derives 0.7% rate
argues money now should be "banked" for future research
rather than radiation protection

Annotated Bibliography

COL80

Author: Collins, John P.

Title: Multiattribute Utility Theory and Environmental Decisions

Journal: Journal of Environmental Engineering Division

Volume: **Date:** 1980 **Page:** 815

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other
Description T	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste T	Other Application	

Additional Comment:

Annotated Bibliography

CUL82

Author: Culver, K.B.

Title: Close-out concepts for the Elliot Lake Uranium Mining Operations

Journal: Management of Wastes from Uranium Mining and Milling

Volume: Date: 1982 Page: 157

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
T		T	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: discussion of close out alter.; costs; emission reduc.

Annotated Bibliography

DIC83

Author: Dickman, P.T., Boland, J.R.

Title: Cost Estimates for Greater Confinement Disposal of Rad. Waste

Journal: Nuc. and Chem. Waste Management

Volume: 4 **Date:** 1983 **Page:** 121-125

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value T	Other costs

Application

Uranium Tailings	Low Level Rad. Waste T	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: trench burial etc.

Annotated Bibliography

DOV83

Author: Dove, James L.

Title: Reclamation of Abandoned Mines in West Virginia
(paper no. 83-2032)

Journal: 1983 Summer Meeting of ASAE

Volume: Date: 1983 Page:

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
	T	
Other Waste	Other Application coal mine waste	

Additional Comment: NUTS
description of problem

Annotated Bibliography

DOW79

Author: Downey Brill, E., Jr.

Title: The Use of Optimization Models in Public-Sector Planning

Journal: The Institute Of Management Science

Volume: 25 **Date:** May 1979 **Page:** 413

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: method, discussion

Annotated Bibliography

EDW75

Author: Edwards, Ward

Title: Use of Multiattribute Utility Measurement for Social Decision Making

Journal: Workshop on Decision Making With Multiple Conflicting Objec.

Volume: Date: 1975 Page: 247

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	SMART

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings

Low Level Rad. Waste

High Level Rad. Waste

Hazardous Waste

Other Mine Waste

Siting

Other Waste

Other Application (see comment)

Additional Comment: administrative Decision Making, land use reg, water use (experts), excellent description, straightforward elicitation method

Annotated Bibliography

EDW77

Author: Edwards, Ward

Title: How to Use Multiattribute Utility Measurement for Social Decisionmaking

Journal: Transactions on Systems, Man, and Cybernetics

Volume: 7 **Date:** May, 1977 **Page:** 326

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	SMART
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application (see comment)	

Additional Comment: see EDW75 (this is the same article)

Annotated Bibliography

EIC76

Author: Eichholz, Geoffrey

Title: Cost-Benefit and Risk-Benefit Assessment for Nuclear Power Plant

Journal: Nuclear Safety

Volume: 17/5 **Date:** 1976 **Page:** 525

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T			

Description	Application	Criteria Value	Other
T	T	T	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application nuclear plant systems	

Additional Comment: cost man-rem.

Annotated Bibliography

ESS82

Author: Ess, Terry

Title: Perspectives of Risk Assessment for Uncontrolled Hazardous Waste Sites

Journal: Management of Uncontrolled Hazardous Waste Sites

Volume: **Date:** 1982 **Page:** 390

Publication Type: CO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T	T	T	risk ass.
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: brief comp. of methods

Annotated Bibliography

FIN85

Author: Fingleton, D., Habegger, L.

Title: Development of The Multi-Attribute Hazard Assessment (MAHAS): Appl. to Energy-Related W. S.

Journal: Air Pollution Control Association

Volume: **Date:** June 16-21,1985 **Page:** 1

Publication Type: CO **Source:** PC

Additional Reference Comment: NUTS

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other risk ass.
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application waste streams	

Additional Comment: degree-of-hazard risk assessment

Annotated Bibliography

FIS67

Author: Fishburn, Peter C.

Title: Methods of Estimating Additive Utilities

Journal: Management Science

Volume: 13/7 Date: 1967 Page: 435

Publication Type: Source:

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other utilities
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: utility measurement description

Annotated Bibliography

FLE82

Author: Fleishman A.B. & M.J. Clark

Title: Eval. Future Detriment from Radioactive Discharges
: Judgements & Implications for Opt. of Protection

Journal:

Volume: Date: 1982 Page: 1

Publication Type: RE Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
		T	time discount

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application rad. discharges	

Additional Comment: time discounting

Annotated Bibliography

FOR79

Author: Ford, Coleen K.

Title: Evaluation Methodologies: A procedure and applic.
to Nuclear Power Plant Siting Methodologies

Journal: Management Science

Volume: 25/1 Date: 1979 Page: 1

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application evaluation of methods	

Additional Comment: comparison of methods

Annotated Bibliography

FOR84

Author: Forgie, D.J.L.

Title: Modelling the cost-effectiveness of sanitary landfill leachate control system

Journal: Civil Engng Syst.

Volume: 1 Date: 1984 Page: 261

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		

Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application
leachate control

Additional Comment: leachate systems - modelling

Annotated Bibliography

GOT81

Author: Gottinger, Hans W.

Title: A Multi-Criteria Cost-Benefit Approach to Energy Technology Assessment

Journal: International Journal of Policy Analysis and Info. Systems

Volume: 5/3 Date: 1981 Page: 211

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application energy alternatives	

Additional Comment:

Annotated Bibliography

HAI74

Author: Haimes, Yacov Y.

Title: Multiobjectives in Water Resource Systems Analysis : The Surrogate Worth Trade Off Method

Journal: Water Resources Research

Volume: 10/4 Date: 1974 Page: 615

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: comparison of tech. - surroggate worth tradeoff; - non inferior sec.; mathematical derivation

Annotated Bibliography

HAR86

Author: Hart, Stephen S.

Title: Disposal alternatives for the Denver radium processing waste Superfund site

Journal: Geotechnical and Geohydrological Aspects of Waste Management

Volume: Date: Feb., 1986 Page: 547

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	matrix weight.
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
	T	
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: radium wastes: Denver
simple weighting evaluation matrix

Annotated Bibliography

HIL83

Author: Hill, D.

Title: High-Level Radioactive Waste Management

Journal: Radioactive Waste Management

Volume: 5 Date: 1984 Page: 41

Publication Type: CO Source: PC

Additional Reference Comment: abstract only

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: general description of various roles (public, gov.,etc)

Annotated Bibliography

HIP82

Author: Keith W. Hipel

Title: Fuzzy Set Methodologies in Multicriteria Modelling

Journal: Fuzzy Information and Decision Processes

Volume: Date: 1982 Page: 279

Publication Type: BO Source: PC

Additional Reference Comment: ed.Gupta&Sanche

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other fuzzy set
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: Waterloo study - good overview

Annotated Bibliography

HOB80

Author: Hobbs, Benjamin F.

Title: Multiobjective Power Plant Siting Methods

Journal: ASCE Journal of the Energy Division

Volume: 106 **Date:** Oct. 1986 **Page:** 187

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	screening
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
		T
Other Waste	Other Application	

Additional Comment: comparison of methods

Annotated Bibliography

HOB80a

Author: Hobbs, Benjamin F.

Title: A Comparison of Weighting Methods in Power Plant siting

Journal: Decision Sciences

Volume: 11 Date: 1980 Page: 725

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	weighting meth.

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste

Hazardous Waste	Other Mine Waste	Siting
		T

Other Waste	Other Application
	nuclear plant

Additional Comment:

Annotated Bibliography

HOR85

Author: Horsak, Randy D.

Title: Selection & Eval. of Hazardous Waste Disposal Sites Using Fuzzy Set Analysis

Journal:

Volume: Date: 1985 Page: 2

Publication Type: CO Source: PC

Additional Reference Comment: see also HOR85a

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste

Hazardous Waste	Other Mine Waste	Siting
T		

Other Waste	Other Application

Additional Comment: fuzzy set analysis

Annotated Bibliography

HOR85a

Author: Horsak, R.D., Sam A. Damico

Title: Selection and Evaluation of Hazardous Waste
Disposal Sites Using Fuzzy Set Analysis

Journal: Journal of Air Pollution Control Association

Volume: 35/10 Date: 1985 Page: 1081

Publication Type: JO Source: PC

Additional Reference Comment: see also HOR85

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
T		
Other Waste	Other Application	

Additional Comment: fuzzy set analysis

Annotated Bibliography

HOW81

Author: Howard, Ronald A.
Title: Risks of Benefit-Cost-Risk Analysis

Journal: Risk/Benefit Analysis in Water Res. Plan. and Management
Volume: Date: 1981 Page: 135

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other cost/risk anal.
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: cost of risk analysis

Annotated Bibliography

JEN86

Author: Jennings, A.A., Suresh, P.

Title: Risk Penalty Functions For Hazardous Waste Management

Journal: Journal Of Environmental Engineering

Volume: 112 **Date:** February, 1986 **Page:** 105

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
			fuzzy set

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste T	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: computer algorithm

Annotated Bibliography

KAT83

Author: Kates, R.W., Kasperson, J.X.

Title: Comparative risk analysis of technological hazards (A Review)

Journal: Proc. Natl. Acad. Sci. USA 80

Volume: Date: 1983 Page: 7027

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
			risk ass.

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: excellent review of r.a. literature

Annotated Bibliography

KEE73

Author: Keeney, Ralph L.

Title: A decision analysis with multiple objectives: the Mexico City Airport

Journal: Economics and Management Science

Volume: 4 Date: 1973 Page: 101

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	MAUT
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application Mexico - Airport	

Additional Comment: clear application of MAUT

Annotated Bibliography

KEE74

Author: Keeney, Ralph L.

Title: Multiplicative Utility Functions

Journal: Operations Research

Volume: 22 Date: 1974 Page: 22

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	MAUT

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application
Mexico Airport Study

Additional Comment: multiplicative utility functions; see also KEE73
mathamatical - justification of add. and mult.
NUTS

Annotated Bibliography

KEE75a

Author: Keeney, R.L. and Keshavan Nair

Title: Decision Analysis for Siting of Nuclear Power Plants -Relevance of Multiattribute Utility Theory

Journal: Proceedings of the IEEE

Volume: 63/3 Date: 1975 Page: 494

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application nuclear plants	

Additional Comment: clear description

Annotated Bibliography

KEE75b

Author: Keeney, Ralph L.

Title: Preference Models of Environmental Impact

Journal: Science for Better Environment

Volume: **Date:** 1975 **Page:** 608

Publication Type: CO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application pest. management	

Additional Comment: good description paper

Annotated Bibliography

KEE75c

Author: Keeney, R.L.

Title: Energy Policy and Value Tradeoffs

Journal: Research Memorandum, IIASA

Volume: 75-76 Date: 1975 Page:

Publication Type: RE Source: LC-CISTI

Additional Reference Comment: s/a KEE77a

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application energy systems	

Additional Comment: see KEE77a

Annotated Bibliography

KEE77a

Author: Keeney, Ralph L.

Title: The Art of Assessing Multiattribute Utility Functions

Journal: Organizational Behaviour & Human Performance

Volume: 19 Date: 1977 Page: 267-310

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application energy systems	

Additional Comment: discussion/appl. to obtain utility functions

Annotated Bibliography

KEE77c

Author: Keeney, R.L. and Keshavan Nair

Title: Nuclear Siting Using Decision Analysis

Journal: Energy Policy

Volume:
Date: 1977
Page: 223

Publication Type: JO
Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	Decision analy.
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application nuclear plants	

Additional Comment: general discussion

Annotated Bibliography

KEE79

Author: Keeney, Ralph L.

Title: Evaluation of Proposed Storage Sites

Journal: Operations Research

Volume: 27   Date: Jan.-Feb., 1979   Page: 48

Publication Type: JO   Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	MAUT	Other
Description	Application	Criteria Value		Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application (see comment)	

Additional Comment: water pumping as elect. storage
choice of storage site (10)
good example of MAUT and sensitivity analysis

Annotated Bibliography

KEE81a

Author: Keeney, Ralph L.

Title: Siting Major Facilities Using Decision Analysis

Journal: Operational Research '81

Volume: Date: 1981 Page: 355

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
		T
Other Waste	Other Application	

Additional Comment: general discussion

Annotated Bibliography

KEE81b

Author: Keeney, Ralph L.
Title: Measurement Scales For Quantifying Attributes
Journal: Behavioral Science: J. Society for Gen. Sys. Research
Volume: 26 Date: January, 1981 Page: 29

Publication Type: Source:

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	quant. attrib.

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application nuc. plant siting	

Additional Comment: set attribute scales, general discussion

Annotated Bibliography

KEE83

Author: Keeler, Emmett B., and Cretin, Shan

Title: Discounting of Life-Saving and Other Nonmonetary Effects

Journal: Management Science

Volume: 29 Date: Mar., 1983 Page: 300

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other

Description	Application	Criteria Value	Other
		T	discounting

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: discussion of discounting of nonmonetary effects
argues equal rates for C and E
lower rate for E not justified

Annotated Bibliography

KEL85

Author: Kelly, G.N. and J.A. Jones

Title: Relative Importance of Collective & Ind. Doses
from Routine Releases of Radioactive Mat. to Atm.

Journal: Ann. Nucl. Energy

Volume: 12/12 Date: 1985 Page: 665-673

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other

Description Application Criteria Value Other discussion

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application nuclide emissions

Additional Comment: discussion on critical group versus pop. dose

Annotated Bibliography

KEN86

Author: Kenanga, Eugene E.

Title: Assessing chemical hazards

Journal: Environmental Science Technology

Volume: 20 Date: 1986 Page: 660

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other chem. hazards

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: evaluation of chemical hazards

Annotated Bibliography

KIR82

Author: Kirkwood, C.W.

Title: A Case History of Nuclear Power Plant Site Selection

Journal: J. Opl. Res. Soc.

Volume: 33 Date: 1982 Page: 353-363

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other decision tree
Description	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application nuc. plants	

Additional Comment: MAU similar to Keeney, good intro. discussion, decision tree

Annotated Bibliography

KIR85

Author: Kirkwood, Craig W.

Title: Ranking With Partial Information: A Method and an Application

Journal: Operations Research

Volume: 33 Date: Jan.-Feb., 1985 Page: 38

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
			ranking
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: shaft: borehole plugs,
good description, grouping of alternatives

Annotated Bibliography

KOF80

Author: E. Kofler and P. Zweifel

Title: Dicisions Under Fuzzy State Distribution With An Application to Health Risks of Nuclear Power

Journal: Modeling of Large-Scale Energy Systems

Volume: Date: 1980 Page: 437

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other deci. analysis
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application nuclear power	

Additional Comment: fuzzy set - math formulation

Annotated Bibliography

LAN80

Author: Landa, Edward

Title: Isolation of Uranium Mill Tailings and Their Comp.
Radionuclides From the Biosph.-Some E. Sci. Persp.

Journal: Geological Survey Circular 814

Volume: Date: 1980 Page: 1

Publication Type: RE Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
		T	gen. decomm.

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: discussion of tailings problem in U.S.
useful review of all aspects
geochemistry, decommissioning

Annotated Bibliography

LAT82

Author: Lathrop, J.W., Watson, S.R.

Title: Decision Analysis for the Evaluation of Risk in Nuclear Waste Management

Journal: J. Opl. Res. Soc.

Volume: 33 Date: 1982 Page: 407-418

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	MAUT .

Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: decision analysis for HLRW depositories, multi-group utilities

Annotated Bibliography

LAW86

Author: Lawson, Dennis W.

Title: Options for reclaiming the Gunnar uranium tailings
Saskatchewan, Canada

Journal: Geotechnical & Geohydrological Apects of Waste Management/86

Volume: Date: 1986 Page: 339

Publication Type: CO Source: PC

Additional Reference Comment: abstract only

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: Gunnar options,
general discussion

Annotated Bibliography

LIP82

Author: Lippitt, J.

Title: Worker Safety and Degree-of-Hazard Consideration on Remedial Action Costs

Journal: Management of Uncontrolled Hazardous Waste Sites

Volume: **Date:** 1982 **Page:** 311

Publication Type: CO **Source:** PC

Additional Reference Comment: see LIP86

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
		T	costs

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
T		
Other Waste	Other Application	

Additional Comment: cost : disc. of work in prog. for occ. cost

Annotated Bibliography

LIP86

Author: Lippit, J.

Title: Costs of Remedial Actions at Uncontrolled
Hazardous Waste Sites: Worker H & S Consideration

Journal:

Volume: Date: 1986 Page: 1

Publication Type: RE Source: LC-LAV

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other

Description	Application	Criteria Value	Other
		T	occupational

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste T	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: cost of OHS

Annotated Bibliography

LOB84

Author: Lobner, P.

Title: Optimization of Public & Occup. Radiation Protection at Nuclear Power Plants

Journal:

Volume: Date: 1984 Page: 1

Publication Type: RE Source: LC-LAV

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		

Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application nuclear power plants	

Additional Comment:

Annotated Bibliography

LOC81

Author: Lochard, J.

Title: Environmental Effects: Optimization of Radiation Protection

Journal: Nuclear Safety

Volume: 22 Date: July-Aug., 1981 Page: 484

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T	T		

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application rad. protection	

Additional Comment: discussion of C/B and C/E analysis

Annotated Bibliography

LOM79

Author: Lombard, J., Oudiz, A.

Title: Use of a multiatribute analysis for the optimizing radioactive Release in the PWR Fuel Cycle

Journal: Radiation Protection Optimization: Pres. Exp. & Organization

Volume: Date: Oct. 3-5,1979 Page: 153

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	Electra

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application
entire fuel cycle

Additional Comment: rad. release entire PWR cycle,
good description of Electra

Annotated Bibliography

LOM79a

Author: Lombard, J.

Title: Review Of Some Decision - Aiding Methods

Journal: Radiation Protection Optimization: Pres. Exp. & Methods

Volume: Date: Oct. 3-5, 1979 Page: 56

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T	T	T	Electra.

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings

Low Level Rad. Waste

High Level Rad. Waste

Hazardous Waste

Other Mine Waste

Siting

Other Waste

Other Application
entire fuel cycle

Additional Comment: comparison of methods, EPA data: PWR study, excellent comp.

Annotated Bibliography

MAA82

Author: Maan, M.A.

Title: Cost effective radiation risk management in a generic nuclear plant design

Journal:

Volume:

Date: 1982

Page:

Publication Type: RE

Source: UC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		

Description	Application	Criteria Value	Other
T		T	

Application

Uranium Tailings

Low Level Rad. Waste

High Level Rad. Waste

Hazardous Waste

Other Mine Waste

Siting

Other Waste

Other Application

Additional Comment: $/life (public and occ.)

Annotated Bibliography

MAC80

Author: Macbeth, P.J.

Title: Systematic Selection of Alternatives for Managing Low-Level Radioactive Wastes

Journal: Annual Meeting ANS.

Volume: Date: June, 1980 Page: 364-366

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other

Description Application Criteria Value Other

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste
T

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: general: disposal options

Annotated Bibliography

MAI85

Author: Maimone, Mark

Title: An Application Of Multi-criteria Evaluation In Assessing Municipal S. W. Treatment & Disp. Sys.

Journal: Waste Management & Research

Volume: 3 Date: 1985 Page: 217-231

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other decision sys.
Description T	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste T	Other Application disposal alternatives	

Additional Comment: ordinal, cardinal mix
multiple viewpoint, good paper

Annotated Bibliography

MCA80

Author: McAllister, Donald M.

Title: Evaluation in Environmental Planning - Assessing Envir., Social, Economic, and Political Trade-offs

Journal:

Volume: Date: 1980 Page:

Publication Type: BO Source: LC-EC

Additional Reference Comment:

Evaluation Method

Cost Benefit
Cost Effectiveness
Multi Criteria
Other comparison

Description
Application
Criteria Value
Other

Application

Uranium Tailings
Low Level Rad. Waste
High Level Rad. Waste

Hazardous Waste
Other Mine Waste
Siting

Other Waste
Other Application

Additional Comment: general overview and comparison of various methods too general for this study

Annotated Bibliography

MCN79

Author: McNamee, D.J.,Quinn, D.J.

Title: A Methodology for Analyzing Decisions Regarding Nuclear Waste Disposal

Journal: ANS Transactions

Volume: CO Date: 1979 Page: 386-387

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other decision anal.
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: decision analysis
general discussion

Annotated Bibliography

MEY69

Author: Meyer, Richard F.

Title: Rel. among the Util. of Assets, the Util. of Cons.
and Invest. Strat. in an Uncert., Time-invar. Wld.

Journal: Fifth IFORS Conference

Volume: Date: 1968 Page: 627

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other

Description Application Criteria Value Other

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: technical discussion of discounting alternative in
investment decisions
NUTS

Annotated Bibliography

MUR83

Author: Murkami, S., Maeda, H., Kishiro, S.

Title: A Method to Asses the Multiattribute Utility Fun.
& its Appl. to the Regional Energy Saving System

Journal: Large Scale Systems: Theory & Applications 1983

Volume: Date: July 11-15,1983   Page: 253-258

Publication Type: CO   Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	utility fun.
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application energy management	

Additional Comment: method to assess utility function
isoutility curve

Annotated Bibliography

NAI76

Author: Nair,K.,Smith,W.,Kulkarni,R.

Title: Decision Analysis - A Methodology For Solving Complex Problems In The Utility Industry: B/C Anal

Journal: Proceedings of the American Power Conference

Volume: Date: 1976 Page: 590-606

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other
Description T	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application four applications	

Additional Comment: general description of application & method

Annotated Bibliography

NAI80

Author: Nainis, W. Scott

Title: Methods for Determining the Value of Model Development in Cost/Benefit/Risk Analysis

Journal: R/B Analysis in Water Resources Planning & Management

Volume: Date: 1980 Page: 149-156

Publication Type: CO Source: PC

Additional Reference Comment: NUTS

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		
Description	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: cost/effect of model usage

Annotated Bibliography

NEA84

Author: Nuclear Energy Agency Secretariat

Title: Long-Term Management of Radioactive Waste
Legal, Administrative and Financial Aspects

Journal:

Volume: Date: 1984 Page:

Publication Type: RE Source: LC-CISTI

Additional Reference Comment:

Evaluation Method

Cost Benefit
Cost Effectiveness
Multi Criteria
Other

Description
Application
Criteria Value
Other

Application

Uranium Tailings
Low Level Rad. Waste
High Level Rad. Waste

Hazardous Waste
Other Mine Waste
Siting

Other Waste
Other Application

Additional Comment: useful discussion, but not for this study

Annotated Bibliography

NEW77

Author: Newman, J. Robert

Title: Differential Weighting in Multiattribute Utility
Measurement:When it shouldn't, & does make a diff.

Journal: Organizational Behavior & Human Performance

Volume: 20 Date: December 1977 Page: 312-325

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application auto selection	

Additional Comment: weighting utility, it is required

Annotated Bibliography

OLI84

Author: Olivier, J.P.

Title: Long-term Management of Uranium Mill Tailings

Journal: Radioactive Waste Management

Volume: 4 Date: 1984 Page: 121

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	Hign Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: time discussion; useful paper

Annotated Bibliography

OSB82

Author: Osborne, R.V.

Title: Optimizing Radiation Protection in Management of Uranium Tailings

Journal: Mgmt. of Wastes from Uranium Mining & Milling Proceedings

Volume: Date: 1982 Page: 471

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: optimizing disposal options

Annotated Bibliography

OSB84

Author: Osborne, R.V.

Title: Developments in Defining Objectives for Radioactive Waste Management

Journal: Can. Rad. Prot. Assoc. Annual Meeting

Volume: Date: April 30- May 3 Page: 1

Publication Type: CO Source: PC

Additional Reference Comment: abst./oral

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
	T	T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: discussion of C/B leading to MAUT

Annotated Bibliography

OTW77

Author: Otway, Harry J.

Title: Appl. of a Simple Multiattribute Rating Technique
to Evaluation of Nuclear Waste Dis. Sites: Demon.

Journal:

Volume: 77/31 **Date:** 1977 **Page:** 1

Publication Type: RE **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
		T
Other Waste	Other Application	

Additional Comment:

Annotated Bibliography

OTW77a

Author: Otway, H.J.

Title: Review of Research on Identification of Factors Influencing Social Response to Technological Risks

Journal: IAEA Conference on Nuclear Power and it Fuel Cycle

Volume: Date: 1977 Page: 95

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
			risk ass.

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings

Low Level Rad. Waste

High Level Rad. Waste

Hazardous Waste

Other Mine Waste

Siting

Other Waste

Other Application
nuclear power

Additional Comment: discussion on decision making

Annotated Bibliography

OUD81

Author: Oudiz, A.

Title: A Multi-Attribute Approach to the Rationalisation of Radiological Protection

Journal: Health Physics

Volume: 40 **Date:** 1981 **Page:** 783-799

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	outranking
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application U-cycle	

Additional Comment: numerous arbitrary ranking

Annotated Bibliography

PAS85

Author: Paschoa, A.S.

Title: Reducing Radon Exhalation from Covered Tailings:
Optimization or Cost Effectiveness?

Journal: The Science of the Total Environment

Volume: 45 Date: 1985 Page: 187-194

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application tailings cover	

Additional Comment: limited to radon reduction

Annotated Bibliography

PER85

Author: Perlack, Robert D.

Title: Multi-Objective Decision-Making in Waste Disposal Planning

Journal: Journal of Environmental Engineering

Volume: III/3 Date: 1985 Page: 373

Publication Type: Source:

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	
T		

Additional Comment: mathematical solution; assumed functions

Annotated Bibliography

POC79

Author: Pochin, Sir Edward

Title: Various Problems Connected With The Intro. Of Opt. Procedures Into Practical Decision-Making Process

Journal: Rad. Prot. Optimization: present experience & methods

Volume: Date: Oct 3-5, 1979 Page: 194-215

Publication Type: CO Source: PC

Additional Reference Comment: roundtable dis.

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T			
Description	Application	Criteria Value	Other discussion

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: round-table discussion on optimization procedures focussed mainly on alpha value

Annotated Bibliography

RIC85

Author: Ricci, Paolo F., Rowe, Michael D.

Title: Health and Environmental Risk Assessment

Journal:

Volume: Date: 1985 Page:

Publication Type: BO Source: LC-UNK

Additional Reference Comment:

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other

Description Application Criteria Value Other

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: No relevant papers

Annotated Bibliography

ROG82

Author: Rogers, V.C.

Title: Uranium Mill Tailings Containment Systems Performance and Cost

Journal: Management of Wastes From Uranium Mining and Milling

Volume: Date: 1982 Page: 197

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description T	Application	Criteria Value T	Other

Application

Uranium Tailings T	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: discussion of disposal options

Annotated Bibliography

ROW79

Author: Rowe, W.D.

Title: Optimization - Theory and Practice: US-40CFR190 - A case study

Journal: RAD. PROT. OPT.: Presnt Experience and Methods

Volume: Date: Oct. 3-5, 1979 Page: 12

Publication Type: CO Source: PC

Additional Reference Comment: abst.: NUTS

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other

Description Application Criteria Value Other

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: historical perspective of US-CFR190

Annotated Bibliography

ROY71

Author: Roy, B.

Title: Problems And Methods With Multiple Objective Functions

Journal: Mathematical Programming

Volume: 1 Date: 1971 Page: 239-266

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: mathematical discussions of methods

Annotated Bibliography

ROY83

Author: Roy, B. and D. Bouyssou

Title: Comparison of two decision-aid models applied to a nuclear power plant siting example

Journal: European Journal of Operational Research

Volume: 25 Date: 1986 Page: 200-215

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	out ranking
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
		T
Other Waste	Other Application	
	Nuclear Power Plant	

Additional Comment: Comparison of methods

Annotated Bibliography

SAA80

Author: Saaty, Thomas L.

Title: The Analytical Hierarchy Process: Planning, Priority Setting, Resource Allocation

Journal:

Volume: Date: 1980 Page:

Publication Type: BK Source: LC-unk.

Additional Reference Comment: NUTS

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other

Description Application Criteria Value Other

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: theoretical

Annotated Bibliography

SAL83

Author:	Salmon, E.J.
Title:	Decision Framework For Disposal Of Radioactive Wastes
Journal:	Radioactive Waste Management

Volume: 1 Date: May 16-20, 1983 Page: 357-369

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	dec. system
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: decision support system
DM gets set of data, not one number

Annotated Bibliography

SHE85

Author: Shechter, Mordechai

Title: Economic Aspects In The Investigation Of Ground-Water Contamination Episodes

Journal: Ground-Water

Volume: 23 Date: March/April,'85 Page: 190-197

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	
T	landfill	

Additional Comment: risk: costs: ground-water cleanup

Annotated Bibliography

SHI81

Author: Shimizu, Yoshiaki

Title: Multiobjective Optimization on Rational Expansion of Radioactive Waste Management System

Journal: Annu. Rep. Res. Reactor Inst. Kyoto Univ.

Volume: 14 Date: 1981 Page: 194-200

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
			multi obj.
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
		T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application in plant	

Additional Comment: based on cost

Annotated Bibliography

SHI82

Author: Shih, Chia Shun

Title: Multiattribute Decision-Making Imbedded with Risk Asses. for Uncontrolled Hazardous Waste Sites

Journal: Management of Uncontrolled Hazardous Waste Sites

Volume: Date: 1982 Page: 408

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other
Description	Application T	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste T	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment:

Annotated Bibliography

SHO85

Author: Short, S.M.

Title: Cost/Benefit Anal. & Comparison of Shallow Land Burial & Greater Confinement Disposal

Journal: Waste Management 85'

Volume: 3 **Date:** 1985 **Page:** 455

Publication Type: **Source:**

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria		Other
T				
Description	Application	Criteria Value		Other
		T	cost	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
	T	
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: cost criteria - $/man. rem.

Annotated Bibliography

SI083

Author: Sioshansi, F

Title: Subjective Evaluation Using Expert Judgement: An Application

Journal: IEEE Trans. on Systems, Man and Cybernetics

Volume: 13-3 Date: 1983 Page: 391

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit Cost Effectiveness Multi Criteria Other
sub. evaluation

Description Application Criteria Value Other

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste
T

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application
Plug system for openings

Additional Comment: subjective evaluation scheme: good approach

Annotated Bibliography

SIS83

Author: Siskos, J., Hubert, Ph.

Title: Multi-Criteria Analysis Of The Impacts Of Energy
Alt.: A survey & a new comparative approach

Journal: European Journal of Operational Research

Volume: 13 **Date:** 1983 **Page:** 278-299

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
			Electra

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application elect. gen. methods	

Additional Comment: good review of methods for choosing generation methods

Annotated Bibliography

SL080

Author: Slovic,P.,Fischoff,B.,Lichtenstein

Title: Rating The Risks

Journal: Risk/Benefit Analysis in Water Res. Plan. and Management

Volume: **Date:** 1980 **Page:** 193-217

Publication Type: CO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other fault tree,risk
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: rating risks
risk preception

Annotated Bibliography

SOB81

Author: Sobral, Maria M.
Title: A Multi-criteria Model for Solid Waste Management

Journal: Journal of Environmental Management
Volume: 12 Date: 1981 Page: 97-110

Publication Type: JO Source: PC
Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	
T		

Additional Comment: Waterloo Waste Management

Annotated Bibliography

SOL84

Author: Solomon, Barry D.

Title: A Survey & Critique of Multiobjective Power Plant Siting Decision Rules

Journal: Socio-Economic Planning Sciences - International Journal

Volume: 18/2 Date: 1984 Page: 70

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting T
Other Waste	Other Application nuclear power plants	

Additional Comment: comparison of applications

Annotated Bibliography

SP082

Author: Spooner, Philip A.

Title: Pollution Migration Cut-Off Using Slurry Trench Construction

Journal: Management of Uncontrolled Hazardous Waste Sites

Volume: Date: 1982 Page: 191

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
		T	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application waste surround	

Additional Comment: slurry trench costs

Annotated Bibliography

STA77

Author: Starr, M and Seleny, M. (ed.)

Title: Studies in Management Sci.; Multiple Criteria Decision Making

Journal:

Volume: 6 Date: 1977 Page: 326

Publication Type: BK Source: LC - CISTI

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: highly theoretical - few applications

Annotated Bibliography

STC82

Author: St. Clair, Ann C.

Title: Dev. of Framework for Eval. Cost-Effect. of Remdial Actions at Uncontrolled Haz. Waste Sites

Journal: Management of Uncontrolled Hazardous Waste Sites

Volume: Date: 1982 Page: 372

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other comparison
T	T	T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
T		
Other Waste	Other Application	

Additional Comment: good comparison paper

Annotated Bibliography

STI69

Author: Stimson, David H.

Title: Utility Measurement in Public Health Decision Making

Journal: Management Science

Volume: 16/2 Date: 1969 Page: B-17

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other utility
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application grant allocation	

Additional Comment: utility measurement

Annotated Bibliography

STI81

Author: Stillwell, William G.

Title: A Comparison of Weight Approximation Techniques in Multiattribute Utility Decision Making

Journal: Organizational Behvaiour and Human Performance

Volume: 28 **Date:** 1981 **Page:** 62-77

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other weighting tech.
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: comparison of weighting techniques

Annotated Bibliography

SZI82

Author: Szidarovszky, F.

Title: Multiobjective Analysis of Regional Mine Water Control and Environmental Protection

Journal: Section C - Env. Pro. Against Impacts of Mine Water Control

Volume: Date: 1982 Page: 129

Publication Type: CO Source: PC

Additional Reference Comment: abstract only

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
	T	
Other Waste	Other Application	

Additional Comment:

Annotated Bibliography

TH082

Author: Thomas, Jerrell M.

Title: Decision Methods in Risk Analysis

Journal: Nuclear Engineering and Design

Volume: 71 Date: 1982 Page: 413-421

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit T	Cost Effectiveness T	Multi Criteria	Other optimization
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application none	

Additional Comment:

Annotated Bibliography

THO83

Author: Thode, Edward F.

Title: Anal. of Expert Opinion on U-Mill Tailings Remed.
Action(UMTRAP) Alter.: Dec.-Sup.-Sys. Pilot Study

Journal:

Volume: Date: 1983 Page: 1

Publication Type: RE Source: LC-LAV

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other Decision analy.
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment:

Annotated Bibliography

VAN83

Author: Van Dyke, James

Title: Benefit-Cost Aspects of Long-Term Isolation of Uranium Mill Tailings

Journal:

Volume: Date: 1983 Page: 1

Publication Type: RE Source: LC-LAV

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T	T		

Description	Application	Criteria Value	Other
		T	time value

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
T		
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: time discounting (good)

Annotated Bibliography

VIN81

Author: Vincke, Philippe

Title: Preference Modelling: A Survey and an Experiment

Journal: Operational Research '81

Volume: Date: 1981 Page: 341

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application general	

Additional Comment: very general paper including theory

Annotated Bibliography

VU084

Author: Vuori, S.

Title: Applicability of Cost-Effectiveness Approach for Comparison of Waste Management Options

Journal: Risks and Benefits of Energy Systems

Volume: Date: 1984 Page: 353

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
	T		
Description	Application	Criteria Value	Other
	T		

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
	T	T
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: dose type discussion and time integration

Annotated Bibliography

WAT82

Author: Watson, S.R.

Title: Multi-attribute utility theory for measuring safety

Journal: European Journal of Operational Research

Volume: 10 Date: 1982 Page: 77-81

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: general discussion

Annotated Bibliography

WEB81

Author: Webb, G., Fleishman, A., Clark, M.

Title: Optimization Of Protection Of The Public: The Application Of Cost-Benefit Analysis

Journal: The Dose Limit Sys. In The Nuc. Fuel Cycle & In Rad. Protec.

Volume: Date: Oct. 19-23,1981 Page: 589-604

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T	T		ALARA

Description	Application	Criteria Value	Other
T		T	

Application

Uranium Tailings

Low Level Rad. Waste

High Level Rad. Waste

Hazardous Waste

Other Mine Waste

Siting

Other Waste

Other Application
rad. protection

Additional Comment: cost: health effect, two types of cost
discounting: good discussion

Annotated Bibliography

WEB83

Author: Webb, G.A.M., Hill, M.D.

Title: Selection Of Waste Management Systems And Strategies

Journal: International Conference On Radioactive Waste Management

Volume: Date: May 16-20, 1983 Page: 1-10

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T		T	
Description	Application	Criteria Value	Other
T		T	

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: general discussion - criteria
- methods

Annotated Bibliography

WEB84

Author: Webb, G.A.M., M.D. Hill

Title: Selection of Waste Management Systems and Strategies

Journal: Radioactive Waste Management

Volume: 4 Date: 1984 Page: 61

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
T		T	

Description	Application	Criteria Value	Other
T	T		

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application
nuclear waste (all)

Additional Comment: comparison of methods

Annotated Bibliography

WER84

Author: Werner, James D.

Title: Remedial Action Management and Cost Analysis

Journal:

Volume: Date: 1984 Page: 1

Publication Type: RE Source: LC-LAV

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
Description	Application	Criteria Value	Other
		T	costs

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste T	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: cover, cut off wall, moving, treatment

Annotated Bibliography

W0078

Author: Wood, D.E.

Title: What is Risk Assessment?

Journal: Waste Management '80

Volume: 1 Date: 1980 Page: 67

Publication Type: CO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	risk ass.
Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: non-linearity of utility - general discussion

Annotated Bibliography

ZAD73

Author: Zadeh, Lotfi A.

Title: Outline Of A New Approach To The Analysis Of Complex Systems And Decision Processes

Journal: IEEE Transactions on Systems,Man, and Cybernetics

Volume: SMC-3 Date: January, 1973 Page: 28-44

Publication Type: JO Source: PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria T	Other fuzzy set
Description T	Application	Criteria Value	Other

Application

Uranium Tailings	Low Level Rad. Waste	High Level Rad. Waste
Hazardous Waste	Other Mine Waste	Siting
Other Waste	Other Application	

Additional Comment: definition of fuzzy set
operations in fuzzy set

Annotated Bibliography

ZNO79

Author: Znotinas, Nora M.

Title: Comparison of Alternative Engineering Designs

Journal: Water Resources Bulletin

Volume: 15/1 **Date:** 1979 **Page:** 44

Publication Type: JO **Source:** PC

Additional Reference Comment:

Evaluation Method

Cost Benefit	Cost Effectiveness	Multi Criteria	Other
		T	fuzzy set

Description	Application	Criteria Value	Other
T			

Application

Uranium Tailings Low Level Rad. Waste High Level Rad. Waste

Hazardous Waste Other Mine Waste Siting

Other Waste Other Application

Additional Comment: comparison of fuzzy operations

[illegible] Present Value for Various Times at Various Discount Rates
(Assumed annual rate of 1/a)

Time (yrs)	Discount Rate 0.001	0.005	0.01	0.05	0.1
10	9.9	9.7	9.5	7.7	6.1
100	95.1	78.5	63.0	19.8	10.0
250	221.1	142.5	91.7	20.0	10.0
500	393.3	183.5	99.3	20.0	10.0
750	527.5	195.3	99.9	20.0	10.0
1000	631.9	198.6	100.0	20.0	10.0
2500	917.8	200.0	100.0	20.0	10.0
5000	993.2	200.0	100.0	20.0	10.0
7500	999.4	200.0	100.0	20.0	10.0
10000	1000.0	200.0	100.0	20.0	10.0